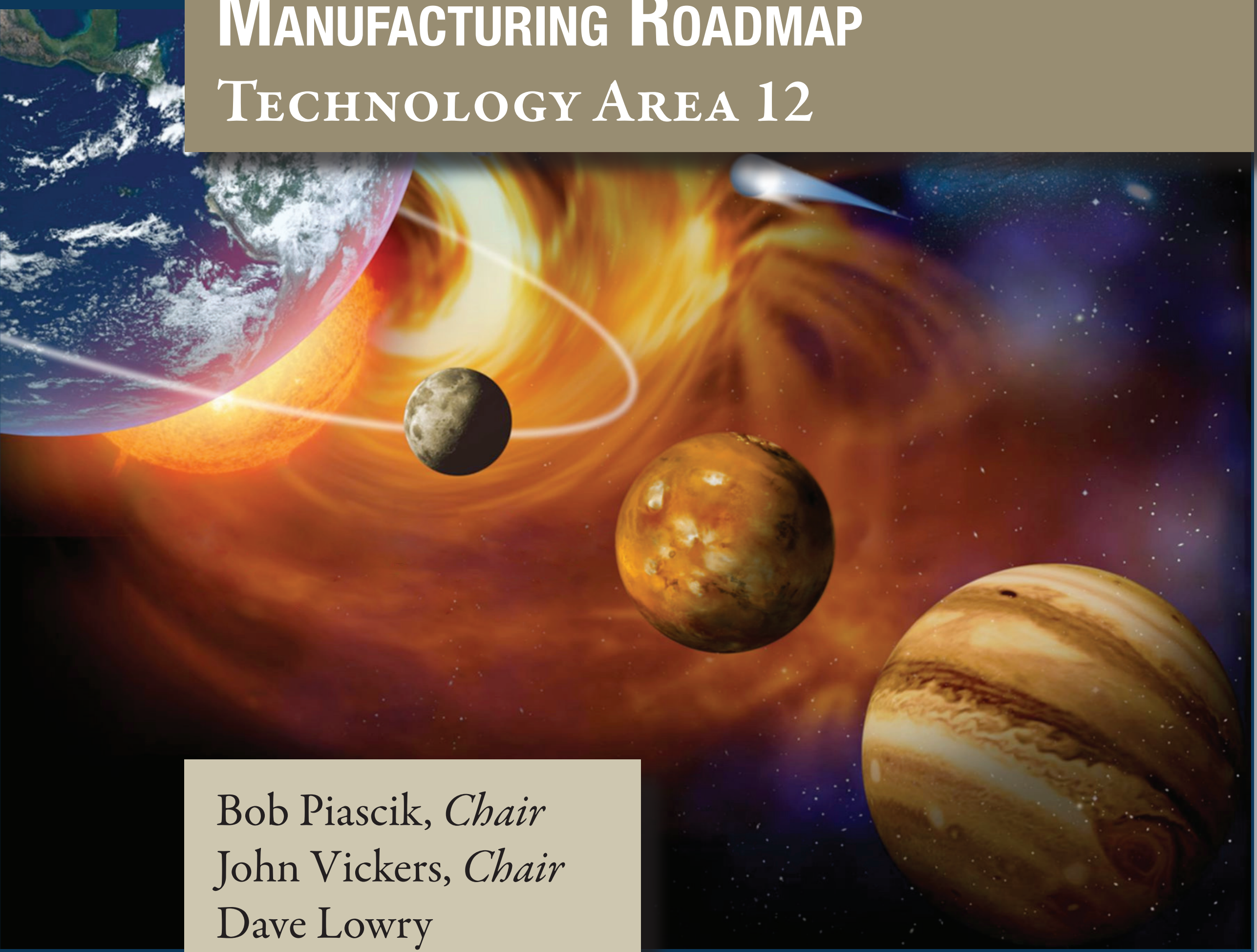
National Aeronautics and Space Administration

DRAFT Materials, Structures, Mechanical Systems, and Manufacturing Roadmap

Technology Area 12



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FOREWORD

NASA's integrated technology roadmap, including both technology pull and technology push strategies, considers a wide range of pathways to advance the nation's current capabilities. The present state of this effort is documented in NASA's DRAFT Space Technology Roadmap, an integrated set of fourteen technology area roadmaps, recommending the overall technology investment strategy and prioritization of NASA's space technology activities. This document presents the DRAFT Technology Area 12 input: Materials, Structures, Mechanical Systems and Manufacturing. NASA developed this DRAFT Space Technology Roadmap for use by the National Research Council (NRC) as an initial point of departure. Through an open process of community engagement, the NRC will gather input, integrate it within the Space Technology Roadmap and provide NASA with recommendations on potential future technology investments. Because it is difficult to predict the wide range of future advances possible in these areas, NASA plans updates to its integrated technology roadmap on a regular basis.

EXECUTIVE SUMMARY

The NASA technology area (TA) roadmap for Materials, Structures, Mechanical Systems and Manufacturing (MSMM) addresses the research and technology development strategy and prioritization required to enable and sustain the Agency's needs in aeronautics, science and exploration. The MSMM technology roadmap develops novel cutting-edge technologies that apply to a wide range of NASA strategic goals and agency programs. For the United States to maintain its leadership in the MSMM technologies, it is critical and strategic that NASA pursues a long-term investment strategy to accomplish the vision provided by the enclosed plan.

The technology roadmap contains overarching themes that are related to push / pull technologies and national needs. Multifunctional and lightweight are critical attributes and technology themes required by mission architecture pull. Certification, sustainment and reliability are technology themes that are critical push technologies that address mission gaps. A deliberate viewpoint for many of the technologies within the roadmap was to promote the idea of innovation in MSMM technologies that bring about totally new inventions or discoveries rather than improvement on an existing technology. Many of the roadmap technologies are directly related to National technology needs associated with development of new energy sources, aging infrastructure and environmental concerns. Figure 2 presents the materials, structures, mechanical systems, and manufacturing TA strategic roadmap as briefly described below. The materials roadmap consists of five discipline capabilities: lightweight structure; computational design; flexible material systems; environment (protection and performance); and special materials and processes. The technology capabilities for lightweight structure, flexible material systems and environment address key near and long-term mission technology needs for advanced structures, propellant depot, heavy lift vehicle and critical concepts for human radiation protection. Special materials and processes capabilities will fulfill a spectrum of unique technology needs for both human and science missions. Computational materials capabilities are truly game changing; these advanced technologies will be used for efficient materials design, enable critical understanding of new materials required for robust and cost effective certification methods and provide critical new technologies for game changing sustainment methods that will ensure safe and reliable missions. The structures roadmap consists of five capabilities: lightweight concepts; design and certification methods; reliability and sustainment; test tools and methods; and innovative, multifunctional concepts. Game-changing technologies exist in each of the capabilities that will enable future deep space missions, next-generation aeronautic capabilities, and long-term space travel. Multifunctional structural systems will provide reductions in mass and volume for next generation vehicles. Innovative model-based technologies are fundamental to the improvement of: a) the design, development, test, and evaluation (DDT&E) process (cost, schedule, robustness, & reliability); b) the flight certification process (cost, schedule, and rigor); and c) vehicle sustainment throughout its service life (safety& reliability). These hardware and methods technology products must be developed to achieve NASA's vision for future aero and space missions. The culmination of these products is a Virtual Digital Fleet Leader (VDFL), described in more detail below that provides a Digital Twin of the flight system with comprehensive diagnostic and prognostic capabilities to enable continuous safe operation throughout the service life of system. The mechanical systems roadmap consists of six capabilities: deployables, docking and interfaces; mechanism, life extension systems; electromechanical/mechanical and micromechanisms, design/analysis tools and methods; reliability/life assessment/health monitoring; and certification methods. Mechanism technologies primarily overcome physical limitations due to launch vehicle (LV) constraints and extending mechanism life in harsher environments such as regolith and cryogenic. Deployable methods, especially for precision large rigid structures or flexible materials are the enabling force behind developing the larger systems needed to attain advancements in science and engineering of today and tomorrow. In addition, micro-mechanisms foster a safer environment for our missions to land and explore new worlds. Exciting systems that keep NASA's finger on the pulse of each vehicle are included in the stepping stones of interrelated correlated analysis system and digital certification and their eventual pinnacle of the VDFL. The manufacturing roadmap consists of four capabilities: manufacturing processes; intelligent integrated manufacturing and cyber physical systems; electronics and optics manufacturing process; and sustainable manufacturing. The manufacturing element provides the most important link between technology invention, development, and application. Emphasis is placed on emerging technologies for aerospace centric processing methods, virtual manufacturing methodology, and environmentally forward-looking manufacturing and the transfer of science and technology into manufacturing processes and products. Developing and demonstrating manufacturing technologies enables continually increasing technology readiness needed for NASA to propel promising technologies into cost-effective applications and sustainable missions. One of the most important considerations of any research and technology program is the ability to accelerate and mature technologies to practical applications. The President's science and technology priorities for the FY2012 budget direct agencies to focus resources on R&D in advanced manufacturing. The cross cutting roadmap consists of three capabilities: nondestructive evaluation, model based certification and sustainment methods, and loads and environments. These capabilities are cross cutting between material, structures, mechanical systems and manufacturing as well as with other technology roadmaps. For structures and mechanical systems, nondestructive evaluation and health monitoring techniques are used in every phase of their DDT&E, manufacturing and service life. Enhanced model-based certification will utilize rich instrumentation datasets to facilitate cost-effective system development and ultimately vehicle sustainment with less mass and improved safety.

The two top challenges identified during the roadmap development are related to human radiation protection and reliability technologies. (1) Long term human exploration will require a critical effort for new radiation protection technology, i.e., lightweight radiation absorbing materials, multifunctional structural design and innovative manufacturing. (2) Safe travel to destinations millions of miles from earth will require extreme reliability with acceptable cost. New cross-cutting materials, structures, mechanical systems and manufacturing technologies will be required to ensure highly reliable vehicles/systems. The roadmap introduces an advanced long term concept (vision), Virtual Digital Fleet Leader (VDFL) (a.k.a. Digital Twin), that addresses the technology needs associated with extreme reliability. Eleven roadmap technology capabilities are focused on the VDFL paradigm, refer to Figure 2; while traveling down the eleven technology capability roads, both pull (mission needs) and push (mission gaps) technology products are developed while evolving the revolutionary VDFL vision into engineering practice. The VDFL paradigm integrates (cross cutting) multiple technology capabilities, into a multi-physics, multi-scale simulation of the as-built vehicle or system. The VDFL incorporates high-fidelity modeling and simulation and situational awareness into a real-time-mission-life virtual construct of the flying vehicle or system. The VDFL continuously forecasts the health of the vehicle or system, the remaining useful life and the probability of mission success. The VDFL vision will lead the Agency into a long-term technology development strategy that directs technologists into a 21st century paradigm, develop the critical MSMM technologies essential for the design of lightweight vehicles / systems and will meet future mission needs relative to high reliability with acceptable cost.

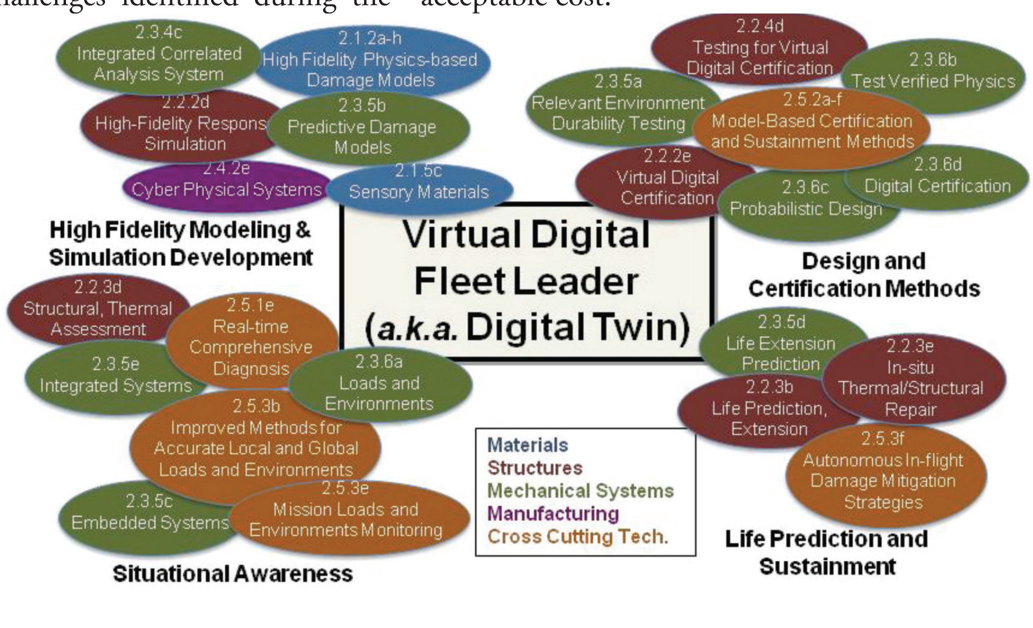
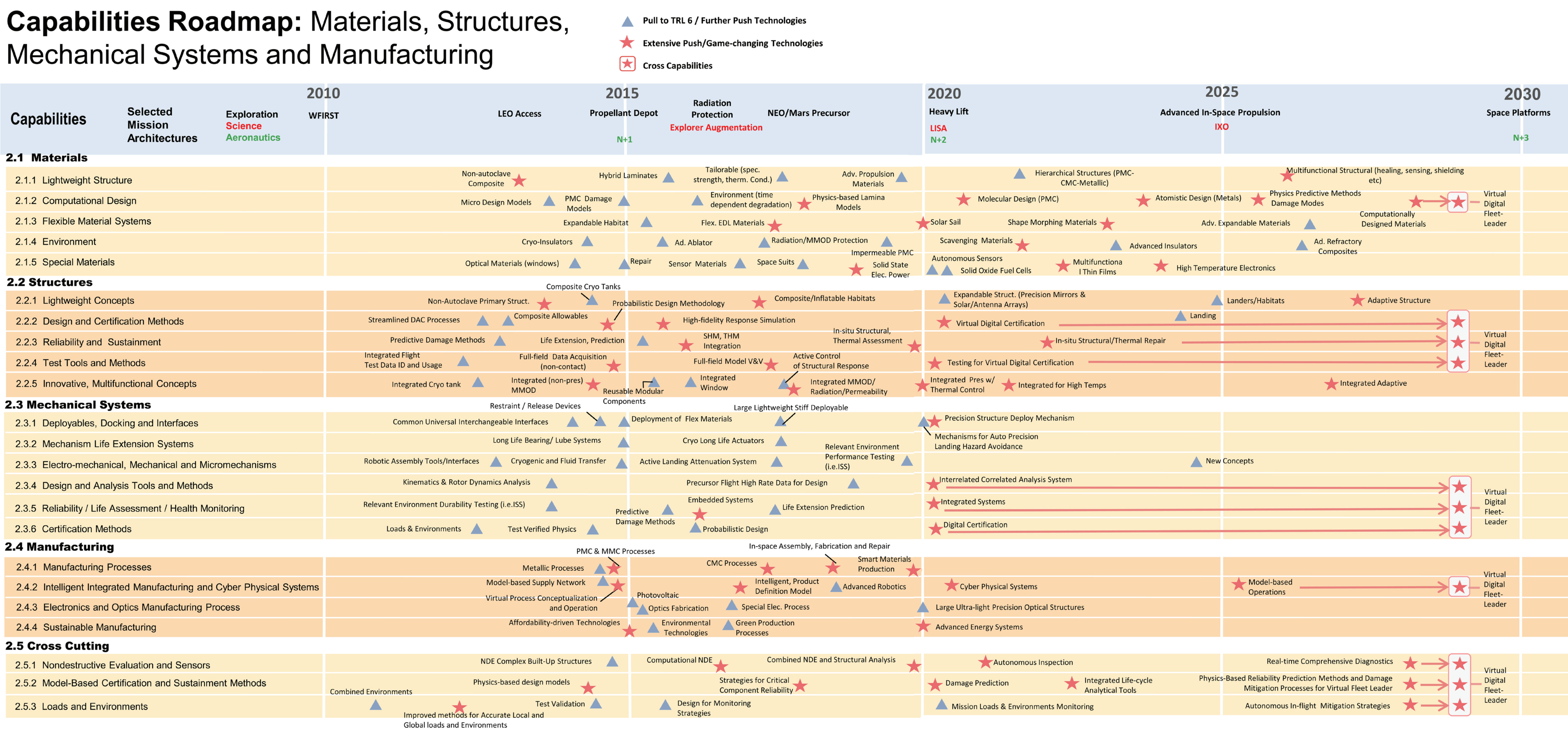


Figure 1. *Integration of technologies within the Virtual Digital Fleet Leader. Color balloons represent the Roadmap TA Capability Products identified in Figure 2.*

Figure 2: *Materials, Structures, Mechanical Systems, Manufacturing and Cross Cutting Strategic Roadmap*



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1. GENERAL OVERVIEW

The MSMM TA portfolio is extremely broad and differs from most other TAs given that it consists of enabling core disciplines, but also encompassing many capabilities that directly impact Agency missions. Technologies identified in this report are truly interdisciplinary and therefore contribute to all of the other 14 TAs. The technology portfolio addresses the Agency's human exploration, science, and aeronautics mission architecture needs for both enhancing and enabling technologies. These are advanced technologies that directly address architecture needs and gaps, new technologies that will significantly enhance mission capabilities, and game changing technologies that will dramatically alter mission capabilities. Further information and descriptions on the various technology items listed in this document are available from the TA Chairs upon request.

1.1. Technical Approach

The MSMM team members were selected from among Agency technology experts in materials, structures, mechanical systems, and manufacturing with background experience ranging from applied to research engineering. The team focused on identifying technical capabilities and technology product areas required to support identified Agency mission needs. In its final form, the major Technology Product Area categories include Materials, Structures, Mechanical Systems, Manufacturing, and Cross-Cutting; each having refined categories that were used to group common technical capabilities as shown in Figure 3. Technology product roadmaps were developed for each technical capability where each symbol is a product is assumed to be at Technology Readiness Level (TRL) 6 maturity (defined in the glossary) and delivered along a time line established by the Agency mission architecture in Figure 2. Pull technology product symbols are shown as blue triangles and directly support major Project milestones. Push technology products are shown as red stars; these products address future mission architecture gaps and represent new enabling technologies the team considered as game changing. It is noted in the roadmap that Pull technologies to TRL 6 may then become push technologies to enable future missions. The expertise of the team was used to generate the roadmap functional model represented in Figure 2. A concerted effort was then conducted to obtain Agency-wide input from more than 100 senior technologists for the final technology portfolio. The team then painstakingly incorporated the senior technologists' inputs. A peer review was conducted by key senior technology stakeholders. This technical approach led the team to a consensus product that resulted in a balanced portfolio to ensure the highest impact products for future NASA missions.

1.2. Benefits

The roadmap technologies not only enable future NASA missions, but they also provide spinoffs that benefit diverse sectors of the economy,

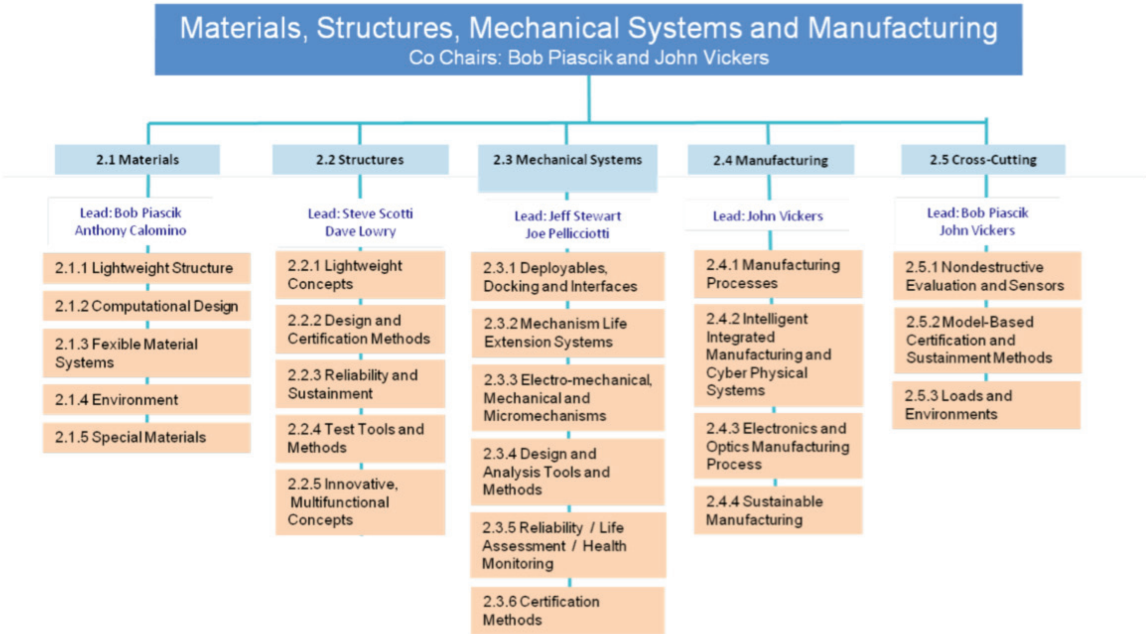

Figure 3. *Work Breakdown Structure (WBS)-Capabilities Breakdown Structure*

increase our global competiveness, and improve national security and quality of life. Energy efficiency and energy independence are facilitated by advanced solar-voltaic cells, superconducting alloys for reduced power transmission losses, and lighter-weight structures, which will reduce transportation fuel costs. Intelligent, "green" manufacturing, recyclable materials, and reusable structures conserve natural resources, eliminate sources of waste, and reduce life cycle costs. In addition, the cyber-physical approaches (e.g., direct, computer-aided-design-driven part fabrication) broaden the United States manufacturing base and facilitate product introduction and improvement. A pervasive use of modeling, simulation, and health monitoring technologies will revolutionize development and operation of civil and military aerospace systems. These technologies will enable more rapid introduction of advanced materials and structural concepts with quantified reliability, reduced maintenance costs, and increased mission safety. Application to non-aerospace systems will help ensure that our national infrastructure (e.g., bridges, dams, and buildings) is properly maintained for safe use.

1.3. Applicability/Traceability to NASA Strategic Goals

The roadmap identifies requirements with extensive applicability for technologies traceable to multiple NASA strategic goals, agency programs and projects and design reference missions/architectures. MSMM technologies and expertise continue to provide critical support to the Space Shuttle's safety of flight and are essential to recertification of ISS structures. MSMM technology and technological knowledge provide fundamental new capabilities for the ever-greater demands of NASA science, exploration, and aeronautics missions such as, validation of thermal protection system (TPS) materials for the Mars entry missions, utilization of International Space Station (ISS) for an advanced materials technology testbed, processing technologies for transforming lunar or asteroid materials for practical uses, and advanced propulsion materials and manufacturing techniques. These missions are highly dependent on such advancements as lighter and stronger materials and methods and reduced manufacturing and operating costs. A specific example of MSMM technology is the friction stir welding technique which allows for the joining of aluminum alloys that cannot be welded by traditional means, first used on the space shuttle external tank; it is now being used to manufacture the Orion Crew Exploration Vehicle, widely by the emerging commercial space sector, and increasingly by the civil aviation sector. These core TAs and their spin-offs will continue to provide sustainable and affordable options that are very important for human space exploration. As a final point MSMM disciplines are at the heart of development of the science, technology, engineering and math workforce initiatives and strategic research partnerships with Universities. This most important benefit of implementing these technologies will be game-changing, disruptive innovation that is stimulated by a growing body of knowledge.

1.4. Technical Challenges

Deep space human and robotic exploration and future aeronautics challenges will require a new suite of advanced technologies to ensure mission success. Table 1 summarizes the MSMM top ten technical challenges that are critical to the Agency's mission; listed are the top two technical challenges and two challenges each for materials, structures, mechanical systems and manufacturing. Also included are three national challenges that will be greatly influenced by the roadmap technologies. The foremost (top two) technical challenges are related to safety and mission success - radiation protection and reliability. The development of human radiation protection is obviously a top challenge; there will be no human deep space travel without sufficient human radiation protection. The technical challenge associated with reliability is not only formidable, but will require new cross cutting paradigms. Reliability will become an enabling consideration for deep space travel; the Agency will no longer be able to afford the low Earth orbit (LEO) strategies developed with legacy tools where reliability has been assured by heavy structural designs, redundant paraphernalia and frequent / rapid supply and resupply capability. Deep space travel will require and a long term focus for the development of extreme reliability technologies that will lead to new paradigms, i.e. Virtual Digital Fleet Leader described in Figure 1. If the agency does not aggressively pursue the development of new technologies that address these challenges in a timely manner, many future Human Exploration, Science and Aeronautics missions will be at risk.

2. PORTFOLIO DISCUSSION

The materials, structures, mechanical systems, manufacturing and cross cutting technology port-

Table 1. *Summary List of Top Technical Challenges*

Challenge (Discipline)	Description
1. Radiation Protection (Top Challenge)	Radiation protection will require the blend of new multifunctional materials and design and unique manufacturing processes
2. Reliability (Top Challenge)	Reliability issues and solutions are truly cross cutting. New technologies will include, (a) Physics based performance modeling (understanding damage/failure modes), (b) Advanced certification methods (design, materials, manufacturing, (c) Sustainment technologies (environment and health monitoring, repair)
3. Advanced Materials (Materials)*	Develop and utilize new materials for specific applications (laminate, extreme environment, healing, sensory, MMOD, etc.)
4. Computational Materials (Materials)*	Mature computational materials technologies for effective low-cost materials and design and physics-based certification/sustainment methods.
5. Multi-functional Structures (Structures)*	Develop robust lightweight structures that are multifunctional (lightweight, insulating, inflatable, protective (radiation and micrometeoroids and orbital debris (MMOD)), inspectable, etc.)
6. Virtual Fleet Leader (Structures)*	Develop first-of-a-kind methodologies for virtual fleet leader real time reliability. Refer to Executive Summary
7. Mechanisms for extreme environments (Mech. Sys)*	Highly (predictive performance) reliable mechanical systems for extreme environments will be required for deep space and long duration missions
8. Precision deployables (Mech. Sys.)*	Precision deployable mechanisms are necessary to enable large observatories
9. Advanced manufacturing process technology (Manufacturing)y*	When realized, improvements will fundamentally change how products are invented and manufactured.
10. Sustainable manufacturing (Manufacturing)*	Sustainable manufacturing is transformational for manufacturing of products that minimizes negative environmental and economic impacts (agency/national competitiveness)
11. Urban Infrastructure (NAE)**	Sustainment methodology (self-healing, sensory, structural health management, hydrogen containment, etc.)
12. Solar Energy**	New materials will be developed for highly efficient solar power
13. Building a Smarter Planet (IBM)**	Practical applications of virtual methods for MSMM multi-disciplinary lifecycle will be directly applicable to every day applications

*These discipline related technical challenges are not prioritized
**These are three national challenges that parallel MSMM technical capabilities

folio is described in the following paragraphs. Each discipline capability is described by a brief summary of major capability TAs identified in the roadmap timeline (Figure 2). The TAs identified (a, b, c, ……) in the paragraphs are listed chronologically so the reader can track each TA along the roadmap timeline. For each technology, a table summarizes the key technology/challenges, what it enables, current TRL and status, and significant steps to achieve TRL 6 for each TA.

2.1. Materials

2.1.1. Lightweight Structure.

The goal of lightweight PMC/Metallic structures is to develop the materials technologies necessary to build the most efficient, optimized structure tailored for a specific application. Achieving this goal requires the development of new materials (polymeric adhesives, matrix resins, metallic alloys) processable by advanced, cost-effective manufacturing methods (Figure 4a). Also, advances in refractory composites (Figure 4b) are critical in providing the extreme thermal environment performance necessary for advanced NASA needs for high temperature applications. This research will provide game changing multifunctional material systems and an integrated structure with seamless interfaces and optimized efficiency. Non-autoclave processing of composites, including vacuum bag only and infusion, provide the capability to fabricate a lightweight structure of virtually limitless size in a single construction process, enabling the efficient delivery of cargo to space and optimized space structure. Complex assembly and joining processes increase costs, weight, and design and manufacturing time. Hybrid laminates utilize two or more different material types com-

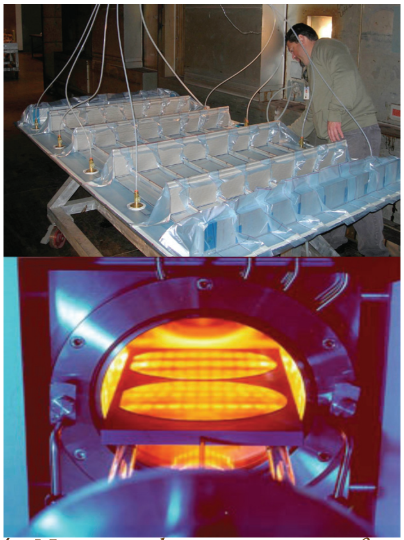

Figure 4. *Non-autoclave composite infusion (top); Advanced ceramics fabrication (bottom).*

bined to deliver the best characteristics of each component. Many material choices for metal, fiber and matrix resin allow tailoring for specific requirements. Tailorable materials are produced with the goal of meeting a specific combination of properties required for an application. A single material property is relatively easy to deliver, but an optimized set of properties is required. Tailorable properties include mechanical strength, stiffness, toughness or damage tolerance, electrical and thermal conductivity, thermal contraction/expansion, environmental and corrosion resistance (temperature, radiation, atomic oxygen, moisture, etc.), and fabricability. To meet requirements for more efficient propulsion systems, materials such as metallic, superalloys, phenolic composites, and refractory composites are designed to be low density with high erosion, pocket spallation and ply lift resistance by tailoring and advanced fabrication techniques. Hierarchical and graded structures are arranged in unique ways to deliver designed performance in response to a threat and its direction. These built-up structures have the capability to resist MMOD and radiation damage from one side while providing thermal insulation and permeation resistance from the other direction in a structure with low areal density and thickness. Multifunctional structural materials utilize advanced computational design and fabrication techniques to deliver a previously unobtainable combination of properties and functions. These systems combine high mechanical and environmental performance with the capability to sense changes or induced damage and the ability to heal that damage and continue performance in the application or system. Lightweight composite and metallic structures enable future NASA missions and are needed to deliver the products presented in the enclosed roadmap. (see Table 2.

2.1.2. Computational Design Materials.

The grand challenge of this emerging technology is to accelerate materials development and predict long-term behavior through basic understanding (linking of physics-based models of materials at multiple length scales) to fully capture the relationship between processing, microstructure, properties and performance. Table 3 summarizes the technology road map products that progress along a systematic path of decreasing length scale and increasing complexity/fidelity technologies. The roadmap products start with first-of-a-kind micromechanics based design tools required for ultra-thin structural materials needed for weight saving design concepts and new multifunctional materials. Longer timelines will be required to develop the understanding of key issues (microcracking and permeability) for composite material design. The determination of the effects of mission specific extreme environments on material performance and revolutionary computational molecular and atomistic-based models required for de-

Table 2. *WBS # 2.1.1 Lightweight Structure*

Key Technology/Challenge	What it Enables	TRL/Current Status	Steps to TRL 6
a. Non-autoclave Composite Develop advanced polymeric matrix resins with high mechanical and functional properties and long out-life.	Large cryotanks built in a single construction step with optimized efficiency and low weight.	TRL 3; Nonautoclave resins have lower mechanical performance, permeation resistance and out-life than needed to construct large structure.	Nonautoclave resins must be matured with properties approaching existing resins but with out-life improvements.
b. Hybrid Laminates Develop hybrid laminates with optimized constituents for multi-functionality.	Aerospace structure that is highly efficient with improved damage tolerance and MMOD and radiation resistance.	TRL 3; Hybrid laminates are currently used in commercial applications but NASA requires unique material combinations to meet needs.	Advanced hybrid laminates combining unique materials being studied and fabricated at small scale must be advanced to larger scale.
c. Tailorable Develop materials with Tailorable properties that meet specific mission needs.	Lightweight and efficient aircraft, launch and space structure to replace current underperforming materials.	TRL 2; Advances are being made but many more mechanical and functional properties can be combined by advanced tailoring.	The potential for tailoring material properties is high but delivery of current tailored products involves limited properties.
d. Advance Propulsion Materials Advance superalloy and ceramic matrix composites for sustained use at temperatures between 1200- 1500°C in high erosion and reactive environments.	Engines and SRMs with improved power and efficiency to more cost effectively deliver cargo to space.	TRL 2; Current materials erode and degrade under the environmental exposure of rocket engines, which limits launch lifting capability.	Advanced CMCs are under investigation at a relatively low level of funding. Potential for advancement is high.
e. Hierarchical Structures Develop hierarchical materials and structural subcomponents to provide integrated, optimized performance.	Significantly reduced weight for aircraft, launch and space structures allowing expanded applications.	TRL 2; Little current effort on complete systems of advanced materials. Substructures using limited advanced materials are under investigation.	Hierarchical materials are being worked at low levels but use will increase when clear system requirements are defined and addressed.
f. Multifunctional Structural Develop material systems that are intelligent designed by computational methods for a detailed assignment.	Multifunctional materials will be highly efficient at meeting specified requirements and will have durability designed in or healing capability available for performance in long duration missions.	TRL 2 for integrated system; Each of the aspects of materials multi-functionality is being advanced, but real payoff is in integrating all of these functions into a smart material/structural system.	Different aspects of multifunctionality are more advanced than others (e.g., sensing vs. healing). Intelligent, self fixing materials with extraordinary lifetimes are needed for long duration missions.

Table 3. *WBS # 2.1.2 Computational Design*

TECHNOLOGY PRODUCT Key Technology/Challenge	What it Enables/Primary / Mission Support	TRL/Current Status	Steps to TRL 6
a MICRO DESINN MODELS Develop first-of-kind life prediction methods for thin metallic materials and PMC damage progression models.	Lightweight Composite Overwrapped Pressure Vessel with thin metallic liners. Understanding PMC microcracking, fiber failure and their influence on damage progression. Needed to design composites that retards permeability. Human and Science Exploration	TRL 3-4; No fracture mechanics methods for life assessment of thin metallic liners. Little understanding of PMC microcracking and progression in extremely constrained configurations. Microcracking currently a constraint on composite tanks	Thin liner model by 2013 and robust modeling by 2015. Microcracking damage progression model by 2015
b. PMC DAMAGE MODELS Predict microcracking formation/propagation, fiber instability and failure and interfacial damage accumulation.	Quantitative models that consider interactive failure modes and their influence on damage progression. Develop lightweight PMC materials for dry and wet structures. Human and Science Exploration	TRL 3-5; Matrix microcracking/failure & fiber failure predictions are of limited accuracy and applicability for matrix-dominated materials/modes or in complex stress states.	Develop resolution or mitigations by 2014
c. ENVIRONMENT (time dependent degradation) Quantify (predict/test) extreme environment capabilities of new materials.	PMC and hybrid materials for cryogenic propellant storage and transport. Long-term durability of load-bearing structures. Human and Science Exploration	TRL 2-5; Classes of materials have been identified. Little understanding of extreme environment usage.	(depending on material)
d. PHYSICS BASED LAMINA MODELS Lamina materials models.	Design of complex multifunctional or hybrid composites. /All Missions	TRL 3-5; Design practices are ad-hoc and rely on extensive testing of specific configurations.	Develop analyses of critical interfaces by 2015
e. MOLECULAR DESIGN MODELS Design and produce PMC resin with predicted enhanced constitutive properties.	Proof of concept for computational design of structural PMCs. All Missions	TRL 2-3; Predictive capabilities for PMC properties in early stage.	Capabilities maturing 2020 to 2025
f. ATOMISTIC DESIGN MODELS Design and produce simply alloy with predicted enhanced constitutive properties.	Proof of concept for computational design of structural alloy .All Missions	TRL 2-3; Predictive capabilities for alloy properties are in very early stage.	Capabilities maturing 2020 to 2025
g. PREDICTIVE MEHTODS DAMAGE MODES Computation materials based models for damage.	Life-cycle predictive capability. All Missions	TRL 2-4; Physics based damage models are being developed at the atomistic and microstructural length scales.	Capabilities maturing 2025 to 2030
h. COMPUTATION DESIGNED MATERIALS Design and produce a structural alloy and a PMC with predicted enhanced properties.	Computational design models for design of structural materials. Optimized materials with degradation understood and predicted throughout their service lives .All Missions	TRL 1-2; Predictive capabilities for design in early stage.	Capabilities maturing 2020 to 2025

velopment of new composites, metallic alloys and hybrid materials with unprecedented properties represents a long-term, but very high pay-off investment. Investment in emerging computational technologies, such as the examples shown in Figure 5, will enable rapid development of tailored materials for optimum performance and the physics-based understand of damage modes needed to ensure extreme reliability, respectively. This technology investment strategy will enable the Agency and the Nation to develop future generation materials and build the essential physics-based understanding to ensure extreme reliability in complex systems through the VDFL concept.

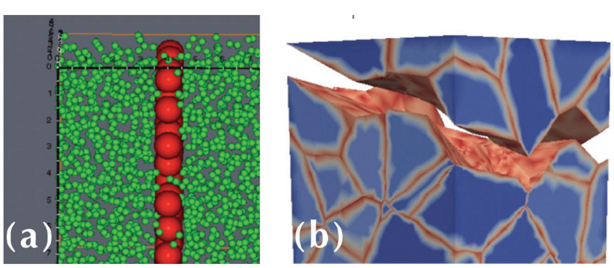

Figure 5. *(a) Thermodynamic model prediction of g' precipitation (in red) in an advanced Ni-based super alloy after 40 hrs at 2000°F. Dr. T.P. Gabb (GRC); ARMD; (b) Simulation of microstructurally small crack growth in an aluminum alloy. Dr. J.D. Hochhalter (LaRC); ARMD.*

2.1.3. Flexible Material Systems.

The focus of flexible material systems is the identification of soft goods or flexible systems that enable the assembly of expandable structures from a small volume to a larger volume through the combined use of rigid linkages and joints with soft thin shells or membranes. The grand challenge of this technology is to offer increased volume, lower mass solution than rigid metal or composite structures through a reliance on the ability to minimize weight and stowed volume without sacrificing operational functionality and reliability. Technology solutions require low-density flexible materials for efficient stowage with deployed systems possessing high strength and stiffness for applications ranging from satellite booms and solar arrays to the construction of temporary shelters and inflatable thermal protection systems. Technology product areas include materials for expandable habitats that leverage proven flexible, softgoods technologies. Higher temperature flexible TPS materials

Table 4. *WBS # 2.1.3 Flexible Material Systems*

Key Technology/Challenge	What it Enables	TRL/Current Status	Steps to TRL 6
a. Expandable Habitat Textile-based materials and thin-film technology for large inflatable or deployable structures.	Lightweight deployed human habitats for space or Mars surface and large space-base observation platforms.	TRL 3; Large structure capability, e.g., McMurdo Antarctica Science Support Center Habitat, ground-based demo for space application.	Ground-based prototypes demonstrated in relevant environment for long-term exposure effects.
b. Flexible EDL Materials Flexible TPSs for hypersonic entry systems.	Large mass payload delivery to Mars or low-heat entries for high-velocity Earth return.	TRL 3; Commercial off-the-shelf (COTS) TPS system has been developed and ground tested.	Orbital fight demonstration of an 8-meter diameter aeroshell to demonstrate fluid-structure interaction stability and control authority.
c. Solar Sail Lightweight aluminized thin film systems for solar sail propulsion.	Fuel-less propulsion using solar wind force on large reflective sails.	TRL 3; CP-1 sails survive space environment for up to 7 years and meet near-term performance needs.	Ripstop construction and relevant space environment testing for long-term duration.
d. Shape-Morphing Materials Shape-Morphing Materials for deployable space structures.	Autonomous deployment and actuated shape control of large space structures.	TRL 2-3; Preliminary identification and process refinement of shape memory materials and self actuating/morphing materials.	Materials designed to actuate hybrid structures featuring embedded SMA must be demonstrated.
e. Advanced Flexible Materials.	Multifunctional softgoods for self actuating and self sensing structures including habitats and large space platforms.	TRL 1-2; Several polymer and metallic material systems show small scale promise of achieving high strain capability and work output.	Systems matured beyond concept stage to incorporate desired functional properties through coating technologies.

are required for atmospheric decelerators. Lightweight solar sail materials are needed for solar propulsion where ultra-thin, metallized polymer films are needed for sails up to 62000 m^2 for realistic mission times. Shape morphing materials offer to revolutionize actuated structures, such as morphing control surfaces as shown in Figure 6 through the use of high strain capable elastic memory polymers and metallic alloys. The development of advanced flexible materials will utilize smart metal alloys and polymers in combination with multifunctional thin films for volume and mass efficient space structures. (see Table 4)

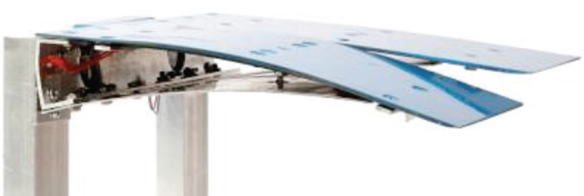

Figure 6. *Variable geometry aerodynamic surfaces using shape morphing materials*

2.1.4. Environment.

The goal of environment protection and performance is to develop the materials technologies necessary to fabricate functional and structural materials capable of maintaining essentially original properties after a defined time period in an extreme environment. The extreme environments encountered include thermal (cryogenic to 2000°C) (Figure 7a), radiation (UV, protons, neutrons, galactic cosmic-ray ions, solar particles) (Figure 7b), MMOD, atomic oxygen, both high and low pressures in inert and oxidizing or caustic atmospheres, regolith (planetary dust) and combinations thereof. Advances in polymeric, ceramic and metallic synthesis and processing lead to novel high-performance structural and functional materials with improved long-term durability. Requirements for environmental performance are ever increasing and unique. Novel materials, such as cryo-insulators with increasing R-value, lower densities and reduced thicknesses and advanced ablators sized for steeper trajectories requiring increased thermal protection will be designed and created. Radiation/MMOD protection, currently parasitic and inefficient, will be designed and fabricated into an efficient multifunctional structural component with long-term durability. Large and lightweight fuel tanks with near zero boil off, which require impermeable PMC, are needed. Game changing extreme durability, necessary for proposed missions, will be delivered by creating in-situ repair materials that fix environmental damage and maintain high performance. Advanced flexible insulators capable of withstanding 1650°C will be delivered for re-entry, aerocapture and sustained hypersonic cruise flight. Refractory materials with improved toughness and easy fabrication into large structure will enable expanded missions. NASA faces unique, extreme environments that can only be managed by increased and consistent investment in novel, multifunctional materials created specifically for these environments. (see Table 5)

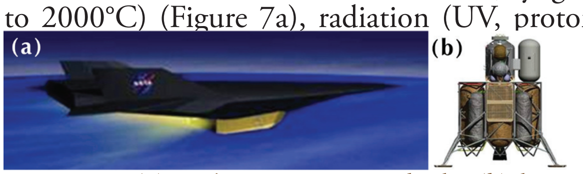

Figure 7. *(a) X-43 Hypersonic vehicle; (b) lunar lander module*

2.1.5. Special Materials.

The goals of this product area are to provide durable, mass-efficient solutions to a broad class

Table 5. *WBS # 2.1.4 Environment*

Key Technology/Challenge	What it Enables	TRL/Current Status	Steps to TRL 6
a. Cryo-Insulators Develop advanced cryo-insulators with high thermal resistivity and low density.	Lightweight, large-scale fuel tanks for in space depots with near zero boil off.	TRL 3-4; Current cryo-insulators have limited insulating capacity on a per weight and thickness basis.	Low-density and thin cryo-insulator for more efficient cryo-liquid storage tank.
b. Advanced Ablator Develop dual-layer or graded ablators that can be optimized to specific missions.	Large-scale lightweight heat shields designs for aggressive entry conditions.	TRL 3; Current ablators are difficult to fabricate in large scale and designed for single point performance.	Large-scale production of advanced dual layer or graded ablators with flight relevant demonstration.
c. Radiation/MMOD Protection Develop integrated spacecraft structural materials with inherent MMOD and radiation shielding capability.	Enables lightweight, efficiently designed spacecraft without the need for parasitic shielding materials.	TRL 2; Currently use bumpers and radiation shielding materials that perform only one function.	Deliver integrated spacecraft structure with inherent multifunctionality.
d. Impermeable PMC Design and fabricate essentially impermeable PMC from advanced matrix resins.	Significant weight savings for large fuel tank enabling a step change in cost of cargo to space.	TRL 3; Current metallic fuel tanks are relatively heavy and potential for weight reduction is limited.	Large-scale demonstration of near zero boil off tank and >20% weight saving.
e. Scavenging materials Raw material manufacturing processes for space reutilization.	Technology enables re-utilization of launched asset mass into space-manufactured components.	TRL 2; Current capabilities include atomization of advanced alloys for powder metallurgy fabrication.	Spaced-based manufacturing capability conceptualized but not demonstrated
f. Advanced Insulators Develop insulators capable of 1650°C performance with improved radiation attenuation.	Long term use of materials on hypersonic cruise structure and more aggressive re-entry trajectories.	TRL 3; Lower temperature performance limiting use time or thermal environment allowable.	Opacified fibrous insulation with extreme temperature capable fibers (1650°C) must be developed.
g. Advanced Refractory Composites Lightweight refractory (1300°C) composite airframes and control surfaces.	Large, single piece, load bearing, reusable heat shields for re-entry.	TRL 3: Limited size capability and expensive manufacturing.	Fabrication techniques for large-scale systems and relevant hypersonic flight demonstration.

of materials that can be used to enhance existing technologies and enable new systems that offer to expand the vehicle the trade space for space and aeronautic vehicles. The product area covers material solutions from the near-term development of more durable and fracture resistant optical materials that will provide lighter window designs, repair materials needed for in-situ repair of both metals and composite structures, sensor materials capable of operating in extreme environments, example, improved space suit materials that will improve protection, mobility, and durability. More efficient, higher temperature thermoelectric and piezoelectric solid-state electric power are needed to generating electricity remotely by converting waste heat and/or mechanical strain into useful energy which, combined with advance sensors, offer autonomous sensors that will eliminating the current wiring complexity for sensor power and conditioning that limit instrumentation. Small-sized, high-power-density solid oxide fuel cells, shown in Figure 8, capable of greater than 2 kW/kg operation offer game-changing electrical power solutions for space, aeronautics, and commercial application. The design of nano-structured multifunctional thin films possessing novel transport, biological, optical and/or electrical properties can be used to form specialized thin film systems and enable the efficient design of large-scaled multi-functional structures. Finally, the development of lightweight, small size high temperature electronic systems that operate beyond 500 ℃ opens vehicle design space be eliminating the need for auxiliary cooling using active systems, heat pipes, or massive heat sinks. (see Table 6)

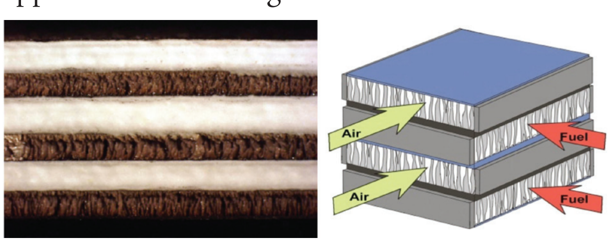

Figure 8. *High temperature solid oxide fuel cells.*

2.2. Structures

2.2.1. Lightweight Concepts.

Lightweight structural concepts are necessary to meet future mission needs in space transportation, in-space, and planetary surface systems and for future generations of efficient aeronautical systems. Low mass is extremely important for in-space and planetary systems because payload mass sizes launch vehicles. These systems will result from innovative structural geometries enabled by new material systems and their cost-effective manufacture as well as the development of an understanding of their mechanics and of the technology necessary for their design, certification and sustainment. Composite structures play an important role in developing lightweight design because of their tailorability to specific requirements. However, for non-terrestrial applications the design, certification and sustainment approaches must be modified from their aircraft heritage (these topics are covered more fully in Sections 2.2.2 and 2.2.3). Also, as additional functions are integrated

Table 6. *WBS # 2.1.5 Special Materials*

Key Technology/Challenge	What it Enables	TRL/Current Status	Steps to TRL 6
a. Optical Materials Durable lightweight optically transparent materials.	Lighter weight, damage-tolerant habitat windows and exposed optical devices.	TRL 2; Current systems utilize heavy, triple redundant systems to ensure safety.	Conceptualized polymeric/glass hybrid and transparent composite systems.
b. Repair Materials and processes for in-situ repair.	Extended lifetimes for space and planetary structures with improved functional reliability.	TRL 2; Current repair materials are limited and repair processes are both labor and time consuming. In addition, current methods have unknown longer functional reliability as in-situ material quality and projected performance assessments need to be developed and matured.	Repair materials, processes, and subcomponent compatibility should be validated in a relevant environment for expected properties. Extended use of materials and processes demonstrated in-situ with anticipated external conditions.
c. Sensor Materials Miniaturized sensors for extreme operation conditions.	Sensing capability for extreme temperature and environmental conditions.	TRL 2-3; Sensors that operate reliably outside a range capability of -40ºC to 300ºC are not readily available.	Emerging SiC and AlN sensor materials technology developed and performance verified.
d. Space Suits Weight-efficient flexible space suit materials.	Enhanced human mobility and endurance for extra-vehicular activity (EVA) exposure.	TRL 2-3; Space suits composed of single-function, multiple material layers.	Develop multi-functional, self healing fibers/fabrics with nano-scaled cooling systems.
e. Solid State Electrical Power Advanced energy-harvesting systems.	Solid-state electric power systems for remote power to sensors and auxiliary electrical systems.	TRL-2; Large-scale electric harvesting systems are operational for low-temperature applications.	Higher temperature capable thermal electric materials and devices matured and miniaturized.
f. Autonomous Sensors Miniature wireless autonomous sensors	Efficient remote sensing and embedded sensors for integrated health monitoring systems.	TRL 2; Manufacture and beadboard demonstration of subcomponents containing modular systems.	Autonomous solid-state concepts must be developed for integrated self monitoring systems.
g. Solid Oxide Fuel Cells Advanced fuel cells	Efficient, high power density electric power generation.	TRL3; Higher power density materials, higher temperature materials are advancing with minimal integrated manufacturing.	Material improvements are required higher quality and optimized properties and mature manufacturing capability.
h. Multifunctional Thin Films Multifunctional thin film technologies.	Functional thin film layers ranging from fractions of a nanometer to several micrometer thickness materials for rigid and flexible components that offer large-scale, multi-functional solutions.	TRL2-4; Main application of thin film construction are electronic semiconductors and optical coatings. Metallic and polymeric materials with specialized thermal-optic and -electric capabilities advancing for thin film technologies.	Manufacturing from atomic to macroscopic scales must be solved to demonstrate discrete function. Constituent material interactions and incompatibilities also must be addressed.
i. High Temperature Electronics Extreme-temperature electronics.	Extreme temperature integrated circuit electronics that operate well beyond the temperature capability window of electronics (-55ºC to 350ºC)	TRL 2: Emerging wide bandgap semiconductors, such as SiC, GaN, AlN are being researched.	Material quality improvement required with mature manufacturing capability

in lightweight concepts (multifunctionality is covered more completely in 2.2.5), the mass benefits increase but at the cost of increased design, certification, and sustainment complexity. Size and cost are additional criteria addressed by this set of capabilities. Manufacturing – especially for composites – is limited by available facility size and the more complicated the design the greater the cost and difficulty of manufacture. So concepts that are enabled by non-autoclave processing of composites and with integrated or low cost tooling are of great importance (see Figure 9). In addition, payload envelope size constraints of launch vehicles must be overcome for future missions. So inflatable habitats and expandable structures that allow for a deployed structure to meet mission requirements (e.g., sufficient habitable volume for crewed missions, or a very large and precise surface for in-space collectors or reflectors) while fitting within the launch payload geometry constraints are important technology needs. (see Table 7)

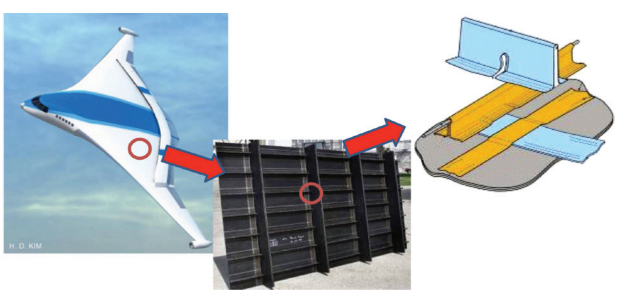

Figure 9. *Non-Autoclave (stitched, VARTM) Primary Structure for Conformal Pressurized Fuselage (ARMD-Subsonics)*

2.2.2. Design and Certification Methods.

Design and certification methods are necessary for development of any structural system. Heritage design methods will, in general, not be applicable to new structural technologies or even to existing technologies used in radically different applications (e.g., composite structures developed for aircraft used in a space application). The Agency must change 20th century based design and certification paradigms; current practices are not able to quantify appropriate factors-of-safety or design the robust tests/models needed

Table 7. *WBS # 2.2.1 Lightweight Concepts*

TECHNOLOGY PRODUCT Key Technology/Challenges	What it Enables/Primary Mission Support	TRL/Current Status	Steps to TRL 6
a. Non-Autoclave Primary Structure Increased outlife/tacklife for OOA prepregs. Infusion issues for VARTM with dry performs. Achieving consistent quality in fabrication.	Enable economic manufacture of large LVs and complex contour aircraft configurations /Aeronautics and Human Exploration	TRL 2-3 for OOA prepreg structures. Under development in NASA Advanced Composite Technology/ ETDP, also being developed by other government agencies. TRL 4+ for VARTM. Primary structure under development, secondary structure is flying on a number of aircraft.	For prepreg, OOA LV structure, need develop large barrel interstage structures For VARTM primary structure, large component fabrication and test.
b. Composite Cryogenic Tanks Improvements in materials to minimize micro-cracking, and better insulations.	Up to 30% of tank weight can be saved by using composites instead of metals./ Propellent Depot and Heavy Lift Exploration system /Human Exploration (Propellant Depot and Heavy Lift)	TRL 4, Intermediate sized (2-3 meter) composite cryogenic tanks have been produced and tested at MSFC.	High cycle and long-term storage tests are needed to verify that permeability is minimized.
c. Carbon Composites/ Inflatable Habitats Improved understanding (Long term material characterization and leak test validation) of softgoods materials to characterize habitat performance. Composite damage tolerance and robustness including NDE of joints and bonds.	Dramatic increases in volume for crew habitat with potentially less launch mass of the primary structure and improved radiation protection /Human Exploration (NEO- Mars Precursor)	TRL5, Bigelow has 2 small inflatable modules in space. Composites in widespread use in aeronautic primary structures but not in any space habitation applications.	Shell-to-Core Interface Technology & Process Development.
d. Expandable Structures Precision position knowledge, integral distributed actuation.	Deployable structure with high precision - may offer a lightweight replacement for traditional pointing and alignment mechanisms. / Science (Space Platforms)	TRL Depends on application.	Once the specific application is defined, the two steps would be design and analysis followed by fabrication and test of prototypes.
e. Landers/Habitats Characterization of inflatable and composite structures for long-term exposure to the space environment, permeability, structural health monitoring including leak detection, isolation and repair, radiation protection, permeability and damage tolerance.	Scientific and habitability requirements of a long-duration lunar or planetary mission. /Exploration	TRL Depends upon application	Demonstrations of full-scale and subscale prototypes in a laboratory environment.
f. Adaptive Structures Success of this technology requires the cooperation of multi-disciplines: structures, dynamics, control, instrumentation.	Success for long-term missions. /All Missions	TRL1 Very limited activity	Advances in testing and data collection, automated technique in data analysis and algorithms for interpretation of results in structural health monitoring.

to introduce new lightweight materials and efficient structural designs. A progression of products are developed as described in Table 8 that provide progressively greater capabilities in the ability to design and certify structures using a model-based approach; the emphasis here is to strip away unneeded margin(s) (weight/cost) by using newly developed physics based understanding (advanced predictive models) to quantify and maintain extreme reliability. The coupling of the design and analysis to loads is implicit in these efforts. A balanced mixture of developing high-fidelity analytical tools (see Figure 10), failure prediction capabilities from both deterministic and probabilistic standpoints, and verification of the tools with test data is essential to creating a model-based DDT&E process that can be used with confidence. The "Virtual Digital Certification" capability for structures thus derived will provide a new paradigm for developing and qualifying safe structures - especially those using new materials, designs with little heritage experience, and which may be complicated by multifunctional capabilities - without undue conservatism that causes mass penalties, and in a systematic and cost-effective manner. In addition, this capability provides a strong foundation to the ultimate goal of the "Virtual Digital Fleet Leader" (Fig.1). This cross-cutting capability was described in Section 1 and is shown graphically in Figure 2. (see Table 8)

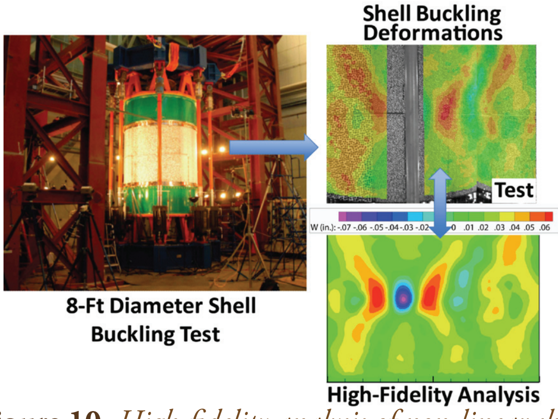

Figure 10. *High-fidelity analysis of non-linear shell buckling and verification with full-field test data (sponsored by NESC and ESMD/CxP).*

Table 8. *WBS # 2.2.2 Design and Certification Methods*

TECHNOLOGY PRODUCT Key Technology/Challenges	What it Enables/Primary Mission Support	TRL/Current Status	Steps to TRL 6
a. Streamlined Design Analysis Cycle (DAC) Processes Integration of several DAC steps into a single software environment.	Performing DAC analysis in much shorter cycle time (trimming months from the present process). / All Missions	TRL4; An integrated environment exists (The Aerospace Corporation) which can be used as an example for the desired system.	Prototype streamlined DAC system
b. Composite Allowables A generic composite damage tolerant sizing methodology from failure models and NDE detection limits.	Significant weight savings for primary structure and lower test costs in the early stages of testing. / All Missions	TRL2-3; A variety of failure models (both empirical and theoretical) exist but no comprehensive sizing architecture exists.	Develop a statistically designed test database for space systems.
c. Probabilistic Design Methodology Characterization of both random and non-random uncertainties from all stages of the design cycle and service life.	Lighter weight designs with quantified reliability for non-heritage concepts, DDT&E resource allocation based effect on reliability/All Missions	TRL4; Basic theory is understood and some commercial software packages are available, but the practical use in design of aerospace structures limited.	Evaluation of various approaches on innovative concepts (in 2.2.1).
d. High-Fidelity Response Simulation Full-scale structural testing along with improved measurement techniques for validation, Improved metrology methods to measure as-built geometry.	Better information early in the design cycle, which reduces reliance on costly development and qualification testing. /All Missions	TRL 4; Some current activities to develop high-fidelity response simulation, (e.g., buckling of cylinders for LV design in NESC Shell Buckling Knockdown Factor Assessment).	Full-scale structural testing of flight-like structures to verify scale-up of model physics and validate predicted results.
e. Virtual Digital Certification Systematic validation and verification (V&V) of models of pristine and degraded structure at all scales in the building block development pyramid with Test Tools and Methods (2.2.4d).	Reduction of costly physical testing, improved confidence for combined environments that cannot be simulated in test. /All Missions	TRL 2; Ongoing efforts to incorporate realistic physics to improve reliability and ease of structural analysis techniques at NASA and elsewhere.	Test validation of large-scale response and damage progression predictions. Development of relevant criteria for certification.
f. Landing Implementing probabilistic techniques, Identification of model validation metrics and verifiable requirements.	Significantly reduce the reliance on expensive full-scale testing for design development & qualification. /All Missions	TRL4-5; Landing dynamic analyses are currently performed at a number of NASA centers for various applications; some efforts ongoing to better quantify uncertainties.	Analysis development at the component level through correlation with test data to characterize uncertainty & confidence of predictions.
g. Virtual Digital Fleet Leader See section 1			

2.2.3. Reliability and Sustainment.

Reliability and sustainment methods are needed to ensure that structures are developed to be reliable and safe, and that these levels of reliability and safety can be maintained throughout the service life of the system. Heritage methods for sustainment are inadequate for two reasons: 1) as in Section 2.2.2, new lightweight materials and multifunctional structural designs have very different characteristics than our experience base, requiring new understandings of mechanisms for damage initiation, damage propagation/structural degradation (see Figure 11), monitoring methods to detect and diagnose damage, and repair methodologies to restore structural integrity, and 2) deep space missions change the paradigm of depot-based sustainment as used for aircraft and the Space Shuttle, or of specially planned resupply/repair missions as is possible with a near-earth space station. Thus sustainment must depend on understanding the mechanics of damage and degradation so that extreme reliability can be designed into the structure, health monitoring that is used to detect damage and integrated with diagnostic and prognostic methods to characterize the damage and the structural residual life, and operational approaches to adjusting mission parameters to extend life or to effect a repair (or a self repair) in the most effective manner. The integration of these technologies into the Virtual Digital Fleet Leader described in Section 1 is the culmination of this reliability and sustainment capability. (see Table 9)

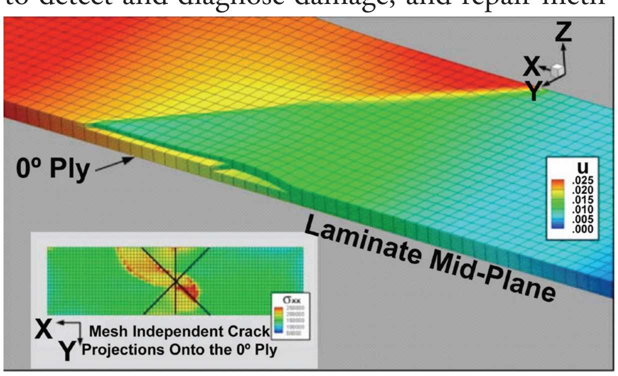

Figure 11. *Predictive damage methods for laminated composites - mesh independent matrix cracking and delamination simulation (Sponsored by ARMD/AvSP).*

2.2.4. Test Tools and Methods.

Improved test tools (laser scanning, vision based, infrared, wireless, etc,) provide new capabilities that better couple with computer-based analytical tools and offer new opportunities for test/model correlation and structural certification by analysis including: a) lower cost and shorter schedule in the qualification phase, b) higher-fidelity correlation and better understanding of structur-

Table 9. *WBS # 2.2.3 Reliability and Sustainment*

TECHNOLOGY PRODUCT Key Technology/Challenges	What it Enables/Primary Mission Support	TRL/Current Status	Steps to TRL 6
a. Predictive Damage Methods Experimental methods to visualize internal damage progression for modeling. Robust, efficient computational algorithms Modeling processes.	Predictive design allowables, accurate simulation of damage initiation and propagation with significantly reduced testing schedule and cost. / All Missions	TRL3-4; High degree of empiricism in damage and failure theories necessitates limiting design space because of significant testing requirements Limited physics-based damage models that are computationally-expensive.	Development and validation of physics-based capabilities (e.g., open-hole tension/compression models for general laminates).
b. Life-Extension Prediction Methods Test data for material characterization in relevant environments to develop, correlate, and validate life prediction models.	Lighter weight from reduced conservatism in the designs. Intrinsic repair can lead to radically different designs. /All Missions	TRL 2-4 for metals and TRL-2 for non-metals,models exist for terrestrial environments (metals); see Predictive Damage Methods for composites.	Environmental durability test data. Correlate models to test data.
c. Structural Health Monitoring and Thermal Health Monitoring (SHM/THM) Integration Development of lightweight sensors and installation techniques; antennas & power sources for wireless systems; supporting data acquisition systems and techniques.	Beneficial weight, cost, & schedule impacts; validation of environmental and structural models; monitoring life & safety issues; flight monitoring for threats. /All Missions	TRL2-4; Varies with SHM/THM measurement technique.	Development and demonstration of practical system for large area monitoring.
d. In-situ Structural, Thermal Assessment Benchmarking of inverse methodology to additional damage data. Realistic testing in a relevant environment.	Facilitate the detection and characterization of damage from sensors during testing and service. /All Missions	TRL2-4; Present solutions are prone to instability and non-convergence. Difficult to determine the location, magnitude, and type of damage from sensors.	Additional damage data and/or modeling results are needed as well as realistic testing in a relevant environment.
e. In-situ Structural/Thermal Repair System-specific extraterrestrial repair material, tools and procedures. Repair validation methodology.	Validated restoration of structural or thermal protection integrity. /Human Exploration	TRL 1+; Limited repair kits for EVA repair of pressure leaks of space station modules and Shuttle TPS.	Varies with system.
f. Virtual Digital Fleet Leader Integration of high-fidelity (d.) and certification (e.) models, service life inspection and health monitoring assessment (d.) data, and life extension prediction methods (b.) with Test Tools and Methods (2.2.4).	Accurate estimates of the residual safety of the structural system to support mission decisions for operation or repair. /All Missions	TRL1+; Digital twin is in concept stage, but constituent capabilities in various stages of development.	Demonstration of fusion preliminary capabilities in several of the constituent capabilities.

al response, c) lighter weight and less intrusive to the vehicle design and operation, and d) better life and repair capability the sustainment phase. A collection of technologies are presented in Table 10 with significant potential to improve the design and certification of structures (in less time with greater accuracy). The coupling of the design and analysis to loads is implicit in these efforts.

Integrated flight test data ID and usage means an integrated package of hardware and software which would allow high-fidelity model correlation at the vehicle level to better understand vehicle response to flight environments (including system damping and modal performance); and then to better incorporate this information into the vehicle certification process (a benefit in terms of cost and schedule). Full-field data acquisition (Non-Contact) systems include point and global measurements and allow direct interface to the design/analysis models. This capability will reduce test set-up and data post-processing time from days to hours while provide a higher-fidelity model correlation capability. Full-field model verification and validation can be incorporated with component and flight test data to improve the vehicle certification process. This provides both quantitative and qualitative model correlation at a vehicle system-wide level and enables virtual digital certification. This better understanding of structural response enables distributed SHM and response control. An LS-Dyna model of a water landing is depicted in Figure 12, where analytical instrumentation is available on a full-field basis to correlate with full-field test tools for a more complete analytical correlation. Testing for Virtual Digital Certification can be enabled by improvements in the preceding technologies. The full-scale test program can be more effective if analytical correlation from the component to full vehicle level is focused on certification by analysis. This focuses on the more effective use of subcomponent and component testing will reduce the amount of full scale testing. Virtual Digital Fleet Leader can then be enabled by extending the Virtual Certification capability into the ongoing life of a multi-use (or long-term single use) of a spacecraft. (see Table 10)

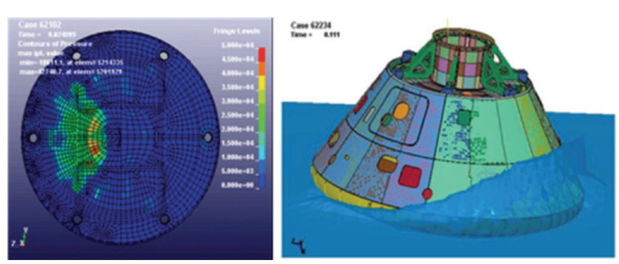

Figure 12. *LS-Dyna Model of a Capsule Water Landing*

Table 10. *WBS # 2.2.4 Test Tools and Methods*

TECHNOLOGY PRODUCT Key Technology/Challenges	What it Enables/Primary Mission Support	TRL/Current Status	Steps to TRL 6
a. Integrated Flight Test Data ID and Usage Analytical Model Correlation	Flight Certification/ All Missions	Hardware aspects TRL 9. Software aspects TRL 6. Integrated system TRL 3 or 4. Currently performed somewhat inadequately at NASA as an integrated technology.	Develop prototype process that incorporates data acquisition and model correlation with full-scale flight test.
b. Full-Field Data Acquisition Implement existing technology on a much larger scale (static and dynamic).	Point and global measurements without the time and cost of instrument installation/calibration/ All Missions	TRL 9 for components, TRL 3 or 4 for full-scale. Used on small-scale tests, not yet demonstrated on full vehicle scale.	Implement existing technology on a much larger scale (static and dynamic).
c. Full-Field Model Verification and Validation Improved understanding of vehicle performance modeling for comparison with flight test instrumentation locations.	Better correlated models for vehicle certification. Lower cost certification process./All Missions	TRL 2-4, This is an improvement on a process that is currently not well performed or integrated in the NASA Human Flight Certification process.	Develop prototype model correlation process that incorporates full field data
d. Testing for Virtual Digital Certification Developing test methods for systematic V&V of models of pristine and degraded structure at all scales in the building block development pyramid w/ Design Certification Methods (2.2.2e).	Virtual Digital Certification./ All Missions	TRL depends on application. Certification by analysis is lacking, especially in large-scale configurations	Once the specific application is defined, test methods at the component to larger scales of the building block pyramid should be developed.
e. Virtual Digital Fleet Leader This represents the testing and model correlation portion of the Virtual Fleet Leader topic discussed in 2.2.3f.	Better understanding of vehicle life in the design phase. Real time adjustment to vehicle life during its mission/ All Missions	TRL 1+ for a full vehicle, higher for components. This work has been performed in a limited, high effort for the return, basis on the ISS.	See 2.2.3f.

2.2.5. Innovative, Multifunctional Concepts.

For deep space missions, a paradigm shift similar to the change from a few day Lunar mission (Apollo) to a multiple year low earth orbit habitat (Space Station), will be a necessary requirement. This means lighter weight, more compact, more autonomous, capabilities must be developed to enable not-too-distant future deep space missions. A suite of such enabling structural technologies is presented in Table 11. The focus of these technologies is more system integration and more autonomy while reducing mass and volume. Examples of the subject technologies includes a research project demo of a lightweight composite tank (Figure 13a), and a metallic foam sandwich panel where hypervelocity Micrometeoroid on Orbit Debris (MMOD) impact capability is integrated into the structure (Figure 13b). (see Table 11)

2.3. Mechanical Systems

2.3.1. Deployables, Docking and Interfaces.

At the heart of this technology is first of all, the capabilities by which NASA can overcome the constraints of launch vehicle fairing size, secondly, the combination and/or separation of spacecraft and spacecraft systems either remotely or with humans in the loop, and thirdly, the development of interfaces that will cost effectively and more reliably streamline system and spacecraft connectivity. Table 12 expands these three categories into more specific key technologies and associated challenges including a common universal interchangeable interfaces approach to interfacing and highly reliable yet fully verifiable; restraint/release devices that will revolutionize NASA's capabilities to deploy, dock, and separate systems of all scales. Additionally, high payoff extensibility is explored in the areas of deployment of flexible materials (see Figure 14), large lightweight stiff structures, mechanisms for auto precision landing and hazard avoidance, and precision structural deployment mechanisms. Specifically and as indicated by the star symbol, the push technology precision structural deployment mechanisms, is game changing. Achieving extremely tight tolerances reaps huge benefits for the science world and when this can

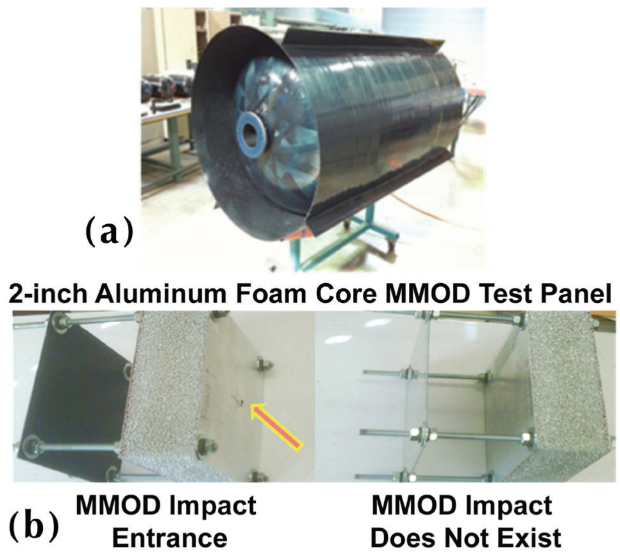

Figure 13. *(a) Structural cryogenic linerless composite tank, and (b) metallic foam core for integral MMOD protection in a sandwich panel.*

Table 11. *WBS # 2.2.5 Innovative, Multifunctional Concepts*

TECHNOLOGY PRODUCT Key Technology/Challenges	What it Enables/Primary Mission Support	TRL/Current Status	Steps to TRL 6
a. Integrated Cryo Tank Address competing thermal isolation and strength/stiffness issues. Integrating primary load paths (especially at joints) Cryotank/sensor integration.	Structural efficiency as reduced volume, reduced weight, reduced schedule, and/or reduced complexity. /All Missions	TRL2, Technologies exist individually to differing levels of maturity, but not developed as a system.	Demonstration of capabilities with a prototype cryo tank.
b. Integrated non-pressurized (MMOD) Manufacturing scale up. Incorporate appropriate MMOD requirements and capabilities.	Structural efficiency as reduced volume, reduced weight, reduced schedule, and/or reduced complexity. /All Missions	TRL2-3, In development stage, though some of the technologies exist individually.	Prototype of MMOD shield for Cryo Fluid transfer project (SOMD proposal).
c. Reusable Modular Components Modular design without undue weight penalties.	Lower life cycle cost. Lower launch mass. Provides flexibility with spares and maintenance. /All Missions	TRL 2+, depends upon application Some Systems studies for lunar-based architecture have been published.	Depends upon application, Demonstrations of full-scale and subscale prototypes in a laboratory environment.
d. Integrated Windows Maintaining Optical Quality with new materials. Integration of windows system into structure.	Structural efficiency as reduced volume, reduced weight, reduced schedule, and/or reduced complexity./Human Space Flight/Habitable Modules	TRL 2-5, Multi-center effort is in progress for materials development at risk for continued funding (see Materials section). Incorporation into structure depends upon outcomes.	Prototype for a DRM with Prototype windows.
e. Active Control of Structural Response Accurately modeling a full scale structure. Providing controls without adding undue weight.	Flexibility of structural design and improved safety in aggressive flight environments. Reduce system mass. /All Missions	TRL 2-5, Depends upon application. Some load alleviation systems are in use in aircraft. Some heavy systems have flown in satellite applications.	Depends upon application, Demonstrations of full-scale and subscale prototypes in a laboratory environment.
f. Integrated Pressurized (MMOD, Radiation, Permeability) Address competing system requirements. Integrating primary load paths (especially at joints)	Structural efficiency as reduced volume, reduced weight, reduced schedule, and/or reduced complexity. /Human Space Flight/Habitable Modules	TRL 2, In development stage, though some of the technologies exist individually.	Demonstration of capabilities with a prototype structure and a TBD DRM.
g. Integrated Pressurized Structure with Thermal Control Address competing system requirements Integrating primary load paths (especially at joints) (thermal management integrated into technologies in 2.2.5f).	Structural efficiency as reduced volume, reduced weight, reduced schedule, and/or reduced complexity. /Human Space Flight/Habitable Modules	TRL 2, In development stage, though some of the technologies exist individually.	Demonstration of capabilities with a prototype structure and a TBD DRM.
h. Integrated Non-pressurized Structure for High Temperatures Address competing thermal isolation and strength/stiffness issues. Integrating primary load paths (especially at joints).	Structural efficiency as reduced volume, reduced weight, reduced schedule, and/or reduced complexity. /All Missions	TRL 2, In development stage, though some of the technologies exist individually (ARMD)	Demonstration of capabilities with a prototype structure and a to be determined DRM.
i. Integrated Adaptive Success of this technology requires the cooperation of multi-disciplines: structures, dynamics, thermal control, instrumentation.	Ability to make thermal-structural adjustments in space without supporting missions. /Human Space Flight/Habitable Modules	TRL1, Conceptual to immature. Depends upon outcome of supporting technologies that are under development	Advances in testing and data collection, automated technique in data analysis and algorithms for interpretation of results in structural health monitoring.

be accomplished via deployable mechanisms then truly great things can happen. So while the other milestones in this technology are required stepping stones, the ultimate pinnacle is deploying large combinations of flexible and lightweight stiff mechanical systems with precise and repeatable results, thereby overcoming the limits of launch vehicle fairing geometry. (see Table 12)

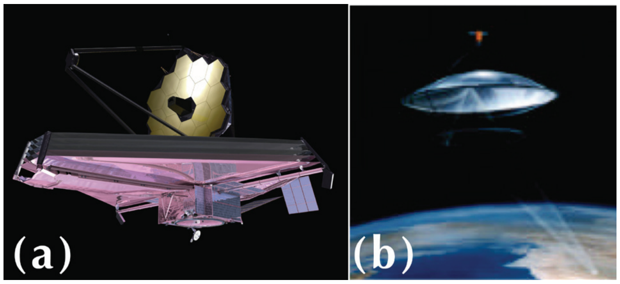

Figure 14. *(a) Deployment of flexible material; JWST sunshield, and (b) 20-25 m class deployable reflector.*

2.3.2. Mechanism Life Extension Systems.

Since many future goals demand long duration missions, safety and reliability are the key targets of this mechanical systems technology. Extra challenging is the fact that most future missions involve environments fraught with very difficult environments like dust problematic regolith and/or extremely cold cryogenic environments. Therefore, as shown in Table 13, the two milestones of long-life bearing/lube systems and cryo long life actuators were chosen. Lengthening mission life and knowing these systems have ample margin opens the gateway to achieving farther-reaching goals much faster.

Table 12. *WBS # 2.3.1 Deployables, Docking and Interfaces*

TECHNOLOGY PRODUCT Key Technology/Challenges	What it Enables	TRL/Current Status	Steps to TRL 6
a. Common Universal Inter-changeable Interfaces Overcome LV geometric constraints and develop simple, lightweight/ reliable universal connections.	Larger deployed structures saving costs, enabling mission design flexibility for unique interfaces, late supplier changes without extensive redesign, interfaces between a wide variety of spacecraft, commonly deployed appendages, non-deployable interfaces.	TRL 4-6 International Docking System Standard/androgynous docking system under development. Many others needed for international partnerships at all scales.	Detailed design/analysis/testing of individual technologies, then combining them properly to produce a workable common interface.
b. Restraint/Release Devices Modeling of pyrotechnic operational dynamics. Decrease size and increase performance of nonpyrotechnic release mechanisms.	Low shock, low mass and highly reliable means of restraint and release of interfaces, systems, spacecraft.	Separation/ Restraint System TRL 2-6 Pyrotechnic Dynamic/Shock Modeling TRL 2-4 Hardware systems achieving all goals have not been demonstrated. Modeling systems for pyrotechnic shock and dynamics are available, but have not been proven to be very accurate in every instance.	Better understand modeling of pyrotechnic operation and performance. Demonstrate/ correlate this understanding in hardware systems.
c. Deployment of Flex Materials Uncertainty of how membranes stow and how they respond in the actual environment, as well as, ultimately accurately predict their deployed shape.	Large deployed systems to overcome LV constraints (solar sails, Gossamer reflectors).	TRL 4-6 Utilization underway (JWST sunshield) yet advancements in this could have high payoffs in multitude of future designs.	Perform scale testing and model correlation leading to full scale testing. Will eventually require zero G testing to complete model correlation.
d. Large Lightweight Stiff Deployable Limited volume of current orbit delivery systems relative to desired size of deployed systems	Overcome limited volume of current LV delivery systems.	TRL 2-6. Has been developed for smaller systems previously, but is required for larger systems.	Complete mechanisms development, deployed model simulation, and ground testing techniques and facilities.
e. Mechanisms for Auto Precision Landing Hazard Avoidance Mechanism integration that allows autonomous spacecraft assessment of several landing parameters	Enables safe reliable landings in non-nominal conditions.	Appendix A TRL 2. Portions currently worked under attenuation systems, but further developments needed to encompass auto select feature changes dependent upon actual terrain/environment encountered.	Appendix B Perform interrelation of mechanisms testing in varying environments and terrains.
f. Precision Structure Deploy Mechanisms Repeatability and predictability of stowing and deploying large structures from a small launch package to very high tolerances	Large reflectors, mirrors, and other position sensitive instruments.	TRL 4-6. Newer requirements/tolerances require development.	Develop requirements, test and perform model correlation to show tolerance feasibility.

Table 13. *WBS # 2.3.2 Mechanism Life Extension Systems*

TECHNOLOGY PRODUCT Key Technology/Challenges	What it Enables	TRL/Current Status	Steps to TRL 6
a. Long-Life Bearing/Lube Systems Overcoming life-limiting properties of current lubrication and components, as well as, the pitfalls associated with harsher environments of dust and cryogenic.	Longer duration missions and increased life for propellant depot type vehicles.	TRL 2 GRC looking at Nitinol-60, GSFC developing hybrid combinations VIM-CRU20, X-30 with silicon nitride, titanium carbide, MSFC investigating improved life testing.	Demonstrate life testing in harsh environments with new lubrication and components.
b. Cryo Long Life Actuators Severe low-temperature environments and their effect on current lubrications and actuator designs.	Low-temp science, planetary, deep-space probe missions.	Magnetic bearings – TRL 4-6. Cryo Bearing Altern. – TRL 4-9. Low-Temp Piezos – TRL 3-4. Magnetostrictive Devices – TRL 3-4. Tribology – TRL 3. Being worked at GRC, GSFC, LaRC, JPL.	Complete cryogenic testing of new systems for required life.

2.3.3. Electro-mechanical,

Mechanical and Micromechanisms encompass the full array of mechanisms small (micro) and large. As highlighted in Table 14, milestones include robotic assembly tools/interfaces which address the development of tools and interfaces that will allow robotic assembly, manipulation, and servicing of spacecraft and spacecraft components; cryogenic and fluid transfer technologies that ensure that critical fluids can be transferred from a carrier (resupply) vehicle to a storage depot, habitable space station, or exploration vehicle for storage or eventual use in long-term space missions; active landing attenuation systems that provide efficient mechanisms to soften the impact load for landing systems on Earth, other planets, or NEO, and potentially reduce system weight by eliminating other heavier passive attenuation systems; relevant environment performance testing (i.e., ISS) which addresses the need for mechanisms performance testing in environments that match more closely the environments in which they will be operated during a mission; and lastly, new concepts (Piezos, etc.) in Electro-mechanical/Mechanical and Micro-mechanisms that enable Space Platforms & Advanced In-space Propulsion by addressing innovative ideas and approaches to actuators, controllers, gears and gearboxes that are needed on virtually every NASA mission. Figure 15 illustrates innovation in small (Microshutters) and large mechanisms.

Table 14. *WBS # 2.3.3 Electro-mechanical, Mechanical and Micromechanisms*

TECHNOLOGY PRODUCT Key Technology/Challenges	What it Enables	TRL/Current Status	Steps to TRL 6
a. Robotic Assembly Tools/Interfaces Complexity and sheer number of systems required for the wide array of tools and systems needed.	In situ buildup/ repair of deep space missions, servicing of LEO satellites.	TRL 2- 9 Multitude of items have flown and are in development currently. Many still required.	Complete development and testing of tools/interfaces.
b. Cryogenic and Fluid Transfer Long life issues of cryogenic actuators for valves and application of cryogenic seals for disconnects.	Resupply to storage depot, space station, exploration vehicle, and long term space missions.	To date no automated fluid coupling system has been demonstrated for cryogenic applications. TRL level for flight fluids transfer is above 6. TRL level for cryogenic applications is 2-3. Design of a space station fluid interface for resupplying O_2 and N_2 is in works	Complete development of fluid coupling system and demonstrate in relative environment and for lifetime required.
c. Active Landing Attenuation System Realtime adaptation of landing systems with enough dampening to account for widely varying landing conditions.	Softened landings and increase success probability of landing cases.	TRL-2 Currently. Designs underway for ORION.	Extension of current designs to future developments needed. Controller logic must be completed and shown viable in analysis models, a sensing strut needs to be built and the combination of controller & strut tested in a relevant environment.
d. Relevant Environment Performance Testing (ie.ISS) Reproducing and combining of required environments into comprehensive tests. Zero G is extremely challenging.	More accurate model correlation, better predictive modeling, and reduce mass through better understanding of system margins.	TRL 2 – 4. Most programs have difficulty combining environments and making them real enough to achieve this.	Develop accurate reproduction of environments. Perform testing.
e. New Concepts Overcome gearing and reliability problems of current actuators and controllers. Making controllers "bus addressable".	Deep space missions due to higher reliability/efficiency simplified control, reduced weight/ complexity of geared systems and actuators.	Most at TRL 4-5 Magnetic gears TRL 3	Detailed design/analysis/testing of individual technologies, then combining them to produce working actuator, and demonstrating a path to an actuator family.

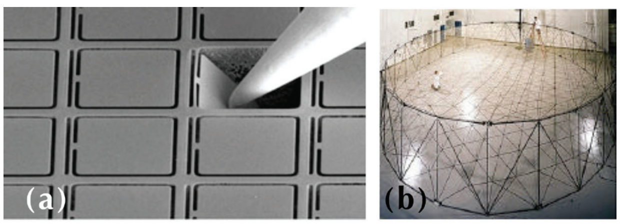

Figure 15. *New concepts with small and large mechanical systems (a) JWST microshutter (micromechanism), and (b) Large deployable mesh antenna.*

2.3.4. Design and Analysis Tools and Methods

These are the critical items and techniques needed to design and analyze any and all Mechanical Systems technologies. Milestones of this technology, as shown in Table 15, include kinematics & rotor dynamics analysis which models emerging materials and structural concepts (e.g., turbomachinery, helicopter rotors, landing systems, and deployment mechanisms) with sufficient fidelity for design and certification. Figure 16 illustrates the current fidelity of typical kinematic analysis for the CEV landing system. Precursor flight high rate data for design which addresses the development of enabling tools and interfaces to increase bi-directional data flow between the various systems and sub-systems; and interrelated correlated analysis system push technology that combines numerical analysis methods of different disciplines to enable creation of a single model of spacecraft mechanical systems in lieu of multiple iterative cycles of serial analyses. This holistic approach would allow for the reduction of overall stack-up of margins across disciplines (e.g., aero loads, vehicle dynamics, structural response); and efficient vehicle/component diagnosis, prognosis, and performance assessment when implemented with a health management system.

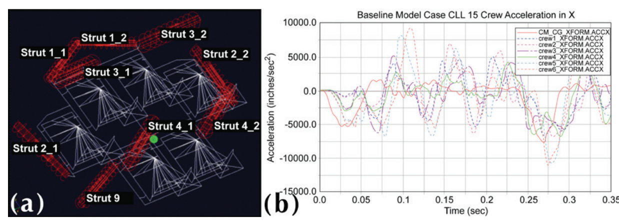

Figure 16. *CEV pallet landing attenuation ADAMS kinematic model (left) and impact acceleration plot (right).*

2.3.5. Reliability / Life Assessment / Health Monitoring

This is the process and set of technologies that will ensure the system will perform as required. Advances in accurately correlating vehicle or system life assessment predictions through the use of health monitoring is a key to fulfilling mission goals with the right tolerances for both the characteristics of the vehicle relative to mission requirements and the costs applied to meet those requirements. Milestones of this technology include

Table 15. *WBS # 2.3.4 Design Analysis Tools and Methods*

TECHNOLOGY PRODUCT Key Technology/Challenges	What it Enables	TRL/Current Status	Steps to TRL 6
(a) Kinematics & Rotor Dynamics Analysis Developing concepts and systems that are not possible to test on the ground.	Improved predictive modeling, weight savings, better performance of concepts not possible to test on the ground.	TRL 1- 6. Being performed at most NASA Centers.	Complete correlated modeling of systems. Prove these systems in hardware.
(b) Precursor Flight High Rate Data for Design Interfaces to the mechanism controller and harsh environments. High data rate needed exclusively for mechanical systems.	Intersystem transfer of data at rates high enough to utilize in real time.	TRL 1-3 Being worked by JSC, GSFC, LaRC and JPL for all systems and sub-systems interface design in every satellite.	Complete hardware development and testing necessary to increase bandwidth and data rate.
c. Interrelated Correlated Analysis System Identifying degree of interrelation/correlation needed for general classes of applications (e.g., serial simulations may be sufficient for aspects of some applications while others may require direct co-simulation of two non-linear codes); and computational methods for combining dissimilar numerical techniques, including nonlinear analyses. Efficient integration of these systems with a health management system.	Reduction of overall stack-up of margins across disciplines (e.g., aero loads, vehicle dynamics, structural response); and efficient vehicle/component diagnosis, prognosis, and performance assessment when implemented with a health management system. Stepping stone to Virtual Digital Fleet Leader.	TRL 1. Not currently being worked.	Complete interrelation/correlation of analysis systems. Integrate health management system into overall analysis system. Prove accuracy of system via testing.
(d) Virtual Digital Fleet Leader (see 2.3.5f)	(see 2.3.5f)	(see 2.3.5f)	(see 2.3.5f)

Table 16. *WBS # 2.3.5 Reliability / Life Assessment / Health Monitoring*

TECHNOLOGY PRODUCT Key Technology/Challenges	What it Enables	TRL/Current Status	Steps to TRL 6
a. Relevant Environment Durability Testing(ie.ISS) Reproduction of relevant environments. Model correlation of mechanisms to effects of environments.	Will allow more accurate model correlation, better predictive modeling, better understanding of system margins, reduced mass and reduced in-service failure rate of mechanisms.	TRL 2-4 Test and Analysis being worked by MSFC, GSFC, Glenn Research Center (GRC), Jet Propulsion Laboratory (JPL), Ames Research Center, White Sands Test Facility, and LaRC	Complete environment reproduction for testing. Perform testing and model correlation.
b. Predictive Damage Methods Accurate determination of manufactured and damaged residual strength of mechanical systems.	Development of more efficient configurations and reduced reliance on testing compared to current practice.	TRL 1-3	Perform testing/model correlation determinations of residual strength.
c. Embedded Systems Miniaturizing and incorporating sensor technology as an integral part of mechanical systems and accurate correlation of system feedback.	Sensing actual loads and other parameters. Have "finger on the pulse" of the system or vehicle.	TRL 3. Deployed and commercial systems. Health monitoring being researched at GRC with the Army and Federal Aviation Administration.	Complete sensor development and perform testing/model correlation.
d. Life Extension Prediction Determination of actual cumulative damage, as well as, establishment of accurate life predictions.	Facilitated design and sustainment of the structure. Concepts incorporating an intrinsic repair capability are a long-term goal.	TRL 1-3	Complete accurate representation of operating environments relative to assessment of cumulative damage. Complete testing and correlation.
e. Integrated Systems Standardization of interfaces.	Health-monitoring interfaces at all levels	TRL 2. Some testing being done where systems are side by side to help with correlation, but current efforts of integration are minimal.	Perform standardization and integration of interfaces and systems. Verify accuracy through testing.
f. Virtual Digital Fleet Leader Development of a digital representation of the entire spacecraft.	Full-up digital representation of vehicle. Provides real-time assessment of vehicle for use in predicting the best next maneuver.	TRL 1. Not currently being worked.	Install instrumentation on spacecraft. Compile data of actual spacecraft systems. Develop integrated system technology. Test and correlate.

relevant environment durability testing (i.e., ISS) which addresses the need for mechanisms durability testing in environments that match more closely the environments in which they will be operated during a mission; predictive damage methods which include science-based damage mechanics, progressive damage analysis methodologies, and system failure models to predict as-manufactured and damaged residual strength of mechanical systems; embedded systems push technology which involve sensing technology development/application, data filtering, signal processing and interpretation in order to provide predictive and condition-based monitoring and prediction of mechanical systems to extend life, avoid failures and assist system operations. Leading goals are timely anomaly detection and prognosis; life extension prediction for mechanical systems which uses cumulative damage from the actual environment to allow for life extension when environments are less extreme than the design case; integrated systems push technology that address the need for health monitoring standardization of interfaces through development of standard integrated systems for health-monitoring capabilities for all systems and sub-systems including power and data; and lastly virtual digital fleet leader push technology that stems from two operating approaches at other government agencies that could be applied to NASA programs. First, the application of sensors in spacecraft which will provide data on the health and reaction of mechanical systems in their service environment (i.e., launch, on-orbit, or even through integration and test and transportation to the launch site). Second, is to use the data obtained from the first element to create a fully digital representation of spacecraft. This digital representation embodies not only the data as it reveals what has occurred to the spacecraft (i.e., diagnosis), but is a fully synthesized technique combining all of our analytical tools to help us predict how a spacecraft will behave in its next maneuver (i.e., prognosis). Although this technology is not currently being worked in NASA specifically, going into ever-changing environments and unknowns will be much easier to handle for future spacecraft if there are tools established which handle forward, predictive systems. Systems such as the Virtual Digital Fleet Leader could make systems and/or course of actions much more survivable and safer. (see Table 16)

2.3.6. Certification Methods

This is the technology for mechanical systems that involves the ability to streamline the test and V&V process from what is now an extensive combination of test and analyses including life testing that often drive project schedules and cost. Other challenges, such as deployable system size and gravity, inhibit the ability to fully test many large deployable systems. As described in Table 17, the milestones included in this technology are loads and environments which address the need to clearly understand the operating environment for the mechanisms; test-verified physics which is the ability to model mechanical systems failure modes such that a system can be designed virtually with the highest probability of success; probabilistic design which utilizes the wealth of test data for various mechanical systems and performance parameters to develop preferred options for hardware design; and lastly the push technology entitled digital certification which is the precursor to the Virtual Digital Fleet Leader. In order to have a complete digital system, we must have the ability to certify subsystems in cyberspace. This is envisioned through the use of hardware health monitoring and telemetry systems that can help to correlate mechanism performance models. Eventually, as our predictive models get better, we might be able to eliminate the cost of large deployable or other mechanical systems testing leading to the virtual digital fleet leader.

2.4. Manufacturing

2.4.1. Manufacturing Processes.

The focus is on emerging technologies that have the potential to significantly improve existing manufacturing methods or processes and lead to entirely new and revolutionary processes to enable production of aerospace products. Ultimately realized improvements will include more rapid production, increased accuracy, defect reduction, reduced costs, more efficient utilization of resources, and reduced environmental impact. Metallic processes through innovative developments such as maturation of new metals processes NASA capabilities contribute to the viability of NASA projects and a domestic aerospace structures manufac-

Table 17. *WBS # 2.3.6 Certification Methods*

TECHNOLOGY PRODUCT Key Technology/Challenges	What it Enables	TRL/Current Status	Steps to TRL 6
a. Loads & Environments Ability to monitor mechanical systems health during loading events.	Improved correlation of kinematic / bearing software, trust life test predicts, reduce weight, design margins & test levels.	TRL 1-3	Develop telemetry scheme for monitoring individual failure modes. Complete combination of individual failure modes to obtain overall system health.
b. Test Verified Physics Modeling mechanical systems' failure modes such that a system can be designed virtually with the highest probability of success.	Significant reduction in cost and schedule if we could accurately predict system failures ahead of hardware build and life test.	TRL 1-3	Accurately determine failure modes of mechanisms. Test and correlate models.
c. Probabilistic Design Obtaining the needed test data for various mechanical systems and performance parameters to develop preferred options for hardware design.	Shift away from expensive tests and verify by correlated analytical data. Reductions in cost and design schedule are evident through meeting functionality requirements with the first hardware build.	TRL 1-3	Obtain test data for mechanical systems. Develop performance parameters.
d. Digital Certification Digitally certifying physical system parameters.	Correlation of mechanism performance models which will ultimately eliminate the cost of large deployable or other mechanical systems testing.	TRL 1. Not currently being worked. Precursor to Virtual Digital Fleet Leader.	Verify single system level digital certification and then develop a module for combining all other system telemetries.
e. Virtual Digital Fleet Leader (see §2.3.5f)	(see §2.3.5f)	(see §2.3.5f)	(see §2.3.5f)

Table 18. *WBS # 2.4.1 Manufacturing Processes*

TECHNOLOGY PRODUCT Key Technology/Challenges	What it Enables	Current TRL/Status	Steps to TRL 6
a. Metallic Processes Provide innovative metal manufacturing processes technologies that have the potential to significantly improve existing manufacturing methods	Efficient primary and secondary structures, cryotanks, and rocket engine components	TRL 5 current practice is stand-alone with many manual processes as opposed to addressing multiple objectives with automation and efficient operations	TRL 5 Emerging large-scale metallic materials, processing, pervasive automation to reduce fabrication/assembly costs and provide recyclability
b. PMC & MMC Processes Develop advanced composites processes (e.g., non-autoclave).	Low cost, Lighter weight, design flexibility, multifunctionality, higher rate production –lightweight structures and radiation shielding	TRL 5 Large autoclave processing, labor intensive	Manufacturing scale-up, processes for cryotanks, and high temp materials, automation to reduce fabrication/assembly costs
c. CMC Processes High quality, manufacturing consistency.	Multiple hot structures applications (e.g., nozzles, flowpath structures, control surfaces and leading edges)	TRL 4 Limited NASA activity at scale	Consistent properties, Scale-up for size, complex curvature, integration
d. In-Space Assembly, Fabrication and Repair Introduction of new materials and methods to fabricate structures in-space.	Fundamental changes to in-space operations	TRL3 Current systems are to laboratory scale	New devices for replacing parts or building new parts in-space
e. Smart Materials Production Development/creation of new manufacturing methods	Adaptability of structures, health monitoring and self-healing	TRL 3 Limited NASA activity, generally led by industry and academia	Significant long-term effort for realization of production ready processes

turing industrial base. Metallic materials are the prime choice of materials by design engineers due to their reliable and predictable mechanical and design properties (Figure 17a).

Polymer matrix composite (PMC) and metal matrix composite (MMC) processes manufacturing technology is crosscutting in many areas and systems. PMC's offer improvements for heavy lift vehicles, and can apply to in-space applications and fueling depots. The largest contribution is mass savings; however, there could be advantages related to controlling thermal expansion and radiation shielding. Composite components are easily adaptable to changes in design. The development of manufacturing processes for PMC's dove-tails with efforts to develop new materials. Ceramic matrix composite (CMC) processes and carbon-carbon (C/C) composites have applications for rocket engine nozzles, air-breathing propulsion flowpath structures, hot structures such as control surfaces and body flaps (both heavily load bearing), as well as leading edges (lightly load bearing). The technology is still not "off the shelf". The biggest gaps include design databases and manufacturing experience. In-space assembly, fabrication and repair (ISAFR) (Figure 17b)technologies greatly advance space exploration capability through reduced risk (i.e., on-orbit repair capability), reduced mass requirements for spare parts and other materials inventory, and reduced operations via automated deployment or fabrication.

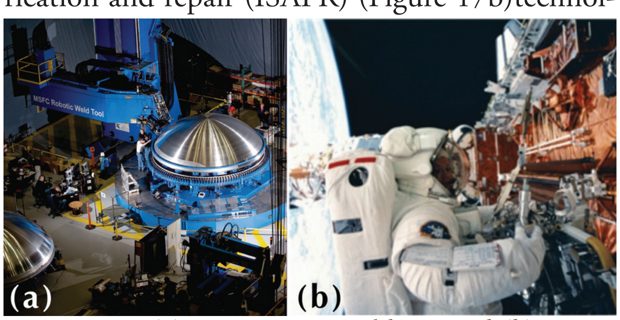

Figure 17. *(a) Friction stir welding; and (b) In-space assembly, inspection and repair.*

ISAFR technologies make possible devices for replacing parts or building new parts (e.g., direct digital mfg) or a means of automatic construction or repairing entire components or systems which can be used anywhere while in-orbit or at extraterrestrial sites. Smart materials production offers materials that have properties that can be changed by external stimuli such as stress, temperature, and electrical energy, including shape memory metals and polymers, temperature-responsive polymers, self-healing materials, and piezoelectric devices. The design and analysis of smart systems, structures, components, and devices using smart materials is generally led by industry and academic research. (see Table 18)

2.4.2. Intelligent Integrated Manufacturing and Cyber Physical Systems.

There is a great opportunity in manufacturing R&D based on innovation for intelligent and integrated manufacturing systems. Over the past two decades incremental improvements in tools for design and manufacturing have produced substantial improvements in productivity and new products. However, today the majority of design to manufacturing is still an ad hoc and empirical process. Dramatic gains in affordability will only come from accelerating the development of breakthrough technologies to develop integrated engineering tools to exploit a models-based approach throughout the product life-cycle. Model-based supply network - sustainable space ex-

Table 19. *WBS # 2.4.2 Intelligent Integrated Manufacturing and Cyber Physical Systems*

TECHNOLOGY PRODUCT Key Technology/Challenges	What it Enables	Current TRL/Status	Steps to TRL 6
a. Model-based Supply Network Terrestrial and in-space collaborative supply networks	Full-knowledge of the design, manufacturing, and operations supply chain	TRL 5 Lack of integrated data stream	TRL 5 Emergent data mining capabilities leverage information from disparate areas
b. Virtual Process Conceptualization and Operation Mathematically accurate models that are linked to manufacturing	Better fidelity simulations being used to define manufacturing, and improved productivity	TRL 5 Currently do not take advantage of data from different sources, models developed late, models from different sources not integrated	Enable model driven equipment and operations to autonomously recognize and respond
c. Intelligent, Product Definition Model Digital product definition contains complete design and manufacturing information	Multiple hot structures applications (e.g., nozzles, flowpath structures, control surfaces and leading edges)	TRL 4 Lack of life-cycle analysis and efficiencies for product development, manufacturing, and sustainment	Lots of research for emerging methodologies for digital product life-cycle model framework
d. Advanced Robotics Next generation of robotics and automation for manufacturing	Operations capable of intelligent actions and responses	TRL 4 Current systems are not connected, flexible or autonomous	Coordination of software, hardware and other technologies
e. Cyber Physical Systems Highly advanced coordination between the system's computational and physical elements	Entirely new manufacturing capability and systems and facilities operated for optimum availability and performance	TRL 4 Limited NASA activity, generally led by industry and academia	Significant effort in scalability from the unit level of to across-the-board operations
f. Model-based Operations Integrates factory, process, reliability and equipment models	Virtual design, checkout, and optimization of processes and physical operations	TRL 5 Currently do not take advantage of data from different sources, models developed late, models from different sources not integrated	Science-based manufacturing environment that enables the virtual evaluation and set-up of new processes and equipment

ploration will require new terrestrial collaborative supply networks and interplanetary supply-chain technology advancement. The overall objective of this effort is to develop an integrated capability for supply network functions as a Virtual Enterprise extending from raw materials, through a network of suppliers, to the manufacturers and the customer (e.g., NASA). Virtual process conceptualization and operation (Figure 18) - This area describes a complete digital manufacturing process built upon mathematically accurate models that drive and support all stages of the product's manufacture. Simulation models linked to visualization environments can enable rapid and accurate evaluation of product and process alternatives, allowing the input of preferences, and real-time feedback.

Intelligent, product definition model - The intelligent product definition is a complete digital product built upon explicit, timeless, computer-sensible models that drive and support all stages of the product's life-cycle. The models capture the full spatial, behavioral, and process description of the product and represent the authoritative source of accuracy for the product definition. All downstream applications across the full product life-cycle are driven from this intelligent product definition. Advanced robotics - The next generation of robotics and automation for manufacturing in aerospace represents a critical technology that offers great advances in productivity, adaptability, accuracy, reliability, and safety. Robotics in manufacturing has historically been led by the automotive sector with disappointingly little transfer of the technology to aerospace. Cyber physical systems – The cyber-physical system is closely related to robotics as in a precise combination of coordination between the system's computational and physical elements. However, the cyber-physical systems of the future will far exceed those of today in terms of adaptability, autonomy, and functionality. Advances in cyber-physical systems for NASA have potential to transform our ability live and work in space. Manufacturing capability in-space remains one of the critical objectives to enable humans to conduct long duration space exploration missions. Model based operations - Model-based operations and control system integrates factory, process, reliability and equipment models with a distributed monitoring and control environment to assure the acceptable operation of the domain (be it machine, factory, or enterprise). NASA should address methods, tools, and components for robust and accurate processes, reliability and equipment modeling systems that respond

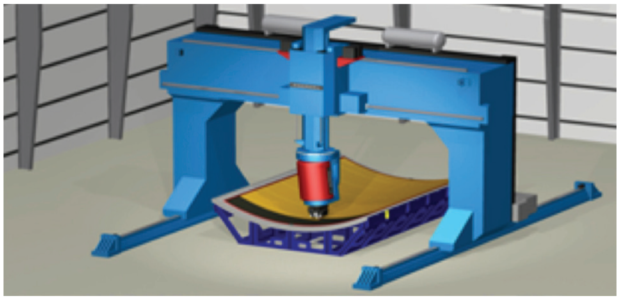

Figure 18. *NASA Visual Process Conceptualization and Operation*

to product and production requirements and will support the design of optimized production systems. (see Table 19)

2.4.3. Electronics and Optics Manufacturing Process.

The commercial electronics industry is leading development in most areas of electronics for NASA applications, however working in partnership with industry and the academic community, results from basic research will lead to better understanding and utilization of electronic materials. Space mirror technology includes the materials used to make the mirror substrates; the processes used to handle, fabricate, and test the mirrors; the mechanical systems used to support the mirrors; and the processes used to certify flight qualification of the mirror systems. (Enabling Future Space Telescopes: Mirror Technology Review and Development Roadmap, April 2009). Photovoltaic research efforts by NASA are a pacing area for human exploration and development of space. New designs and innovative new material systems are needed to improve device efficiencies, and lower cost while reducing weight and maintaining structural integrity. Next-generation solar cells production methodologies require solutions to improve reliability, enhance optical, thermal, or electrical performance. Optics fabrication - Space optical systems require unique advanced processes for manufacturing and metrology of optical surfaces (Figure 19). Innovative mirror substrate materials and manufacturing methods are needed that produce thin mirror substrates that are stiffer and/or lighter than existing materials or methods, including high quality production of the optical quality of X-ray mirrors and substrates. Special electronic processes - Electronic manufacturing processes research for NASA is focused on improving technology, and securing electronics capability for a wide range of missions. Electronics are needed for spacecraft capable of operating in extreme temperature and radiation environments. For the most part research is performed by the space electronics industry and academia with specific guidance and interest by NASA in radiation effects and reliability & failure analysis; 45% of all failures in spacecraft are related to electronics. Large ultra-light precision optical structures research is needed to develop and demonstrate technologies to manufacture ultra-light-weight precision optical systems for very large X-ray, UV/optical or infrared telescopes (i.e., 10+ meters). Potential solutions include new mirror materials such as SiC or nanolaminates or carbon-fiber reinforced polymer; or new fabrication processes such as direct precision machining, rapid optical fabrication, and replication technologies. (see Table 20)

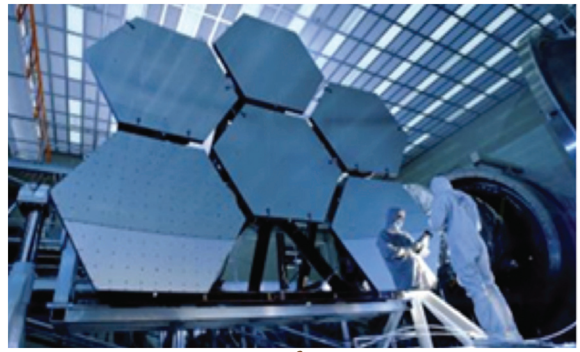

Figure 19. *Optics Manufacturing*

2.4.4. Sustainable Manufacturing.

Sustainable manufacturing is defined as R&D for the design and manufacturing of products that minimize negative environmental and economic impacts. The objective is to identify the sustainability challenges that will have the greatest affect on mission architecture selection and pose the biggest threats and opportunities. Lower manufacturing productions costs can contribute signifi-

Table 20. *WBS # 2.4.3 Electronics and Optics Manufacturing Processes*

TECHNOLOGY PRODUCT Key Technology/Challenges	What it Enables	Current TRL/Status	Steps to TRL 6
a. Photovoltaic New material and processes to improve device efficiencies, and lower cost	Next-generation solar cells production	TRL 5 The commercial electronics industry is leading development in most areas	New cell fabrication processes that provide improved reliability, optical, thermal, and electrical performance
b. Optics Fabrication Improvements for optical systems processes for manufacturing and metrology	Lower cost lighter weight very large space telescopes	TRL 4 Need to produce mirror substrates that are stiffer and/or lighter than existing materials or methods. Metrology resolution is limited.	Improved technologies to manufacture optical quality mirrors and substrates
c. Special Electrical Process New more reliable electronic manufacturing processes capable of operating in extreme temperature and radiation environments	High-efficiency power systems	TRL 5 The commercial electronics industry is leading development in most areas, NASA has interest in special applications	Adopt and improve upon commercial models and processes for use in the production of affordable, advanced NASA systems
d. Large Ultra-light Precision Optical Structures Large precision optical structures, innovative metrology systems.	Precision deployable structures, more thermally-stable structures	TRL 4-5 Current systems are limited in size, needs scale-up	New materials and processes to manufacture ultra-light -weight precision optical systems for very large structures

Table 21. *WBS # 2.4.4 Sustainable Manufacturing*

TECHNOLOGY PRODUCT Key Technology/Challenges	What it Enables	Current TRL/Status	Steps to TRL 6
a. Affordability-driven Technologies New and substitute environmentally sustainable processes	Sustainable manufacturing, mitigates risks from obsolescence	TRL 5 Mostly reactive approach to environmental manufacturing issues	Sustainable design and manufacturing for products that minimize negative environmental effects
b. Environmental Technologies Innovative methods to improve affordability and accelerate program schedules	Enables resource efficiency & effectiveness, and long-term sustainability	TRL 5 Current initiatives are not coordinated, focus is on objectives related to performance	Comprehensive directed approach to emerging processing, and manufacturing technologies to meet affordability goals
c. Green Production Processes New green processes, new materials, and replacement processes.	Mitigates risk and matures readiness.	TRL 5 Significant development needs are widespread.	Proactive steps since materials and processes availability is continually impacted
d. Advanced Energy Systems Technology development for high-efficiency power systems	Technologies applicable to both space exploration and clean and renewable energy for terrestrial applications	TRL 4 Advanced systems are being demonstrated in the laboratory	A combination of advanced materials and materials processing techniques that impact the entire energy sector

cantly to the economic sustainability. Sustainability is critical to NASA and the competitiveness of the Nation. Affordability driven technologies for today's' aerospace design and manufacturing goals focus on mission objectives related to operability, reliability, and performance. Achieving these performance goals is often accomplished at the expense of life-cycle cost. Emerging technologies offer a strategic opportunity to improve affordability and accelerate execution time while performance standards are met. Reduced manufacturing operations (e.g., assemblies/tooling), part count, touch labor, and methods such as direct production of powder-metallurgy of components (e.g., combustion devices) can dramatically reduce the cost of structures. Another area of emphasis is the need for an accelerated plan for the building block approach. Environmental technologies for aerospace materials and manufacturing processes availability are impacted by environmental and safety regulations, pollution prevention goals and related vendor decisions. The aerospace community faces challenges with the availability material supply chains during the life-cycle of a program due to material obsolescence from new regulatory restrictions on production and use of traditional materials. Green production processes for major new manufacturing enterprises and production processes require a focus on environmental impact and sustainability. Today, implementation of green technology processes is slowed by lack of fundamental data, fragmentation of effort, and insufficient R&D programs. R&D for new chemical processes, new polymer and composite materials, paints, coatings, etc., and replacement processes for conventional metal finishing can transform manufacturing. Environmental issues are technically complex and materials changes involve significant program risk. Advanced energy systems provide innovation in materials and process technologies that are critical to achieving the longer term objectives of an energy-efficient and low-carbon world. (Linking Transformational Materials and Processing for an Energy Efficient and Low-Carbon Economy: Creating the Vision and Accelerating Realization, Energy Industrial Technologies Program, February 2010). Renewable energy sources for future terrestrial and space development and energy-related materials and manufacturing for batteries/fuel cells, nuclear energy, and photovoltaics require Agency investment. (see Table 21)

2.5. Cross Cutting

The cross cutting roadmap consists of three important capabilities: NDE and sensors, model-based certification and sustainment methods, and accurate characterization of loads and environments. These capabilities are cross cutting within MSMM as well as with other technology roadmaps. For structures and mechanical systems, NDE and sensors for health monitoring are required in every phase of their DDT&E, manufacturing, and service life. Enhanced model-based certification will utilize rich instrumentation datasets to facilitate cost-effective system development and ultimately vehicle sustainment with less mass and improved safety. Developing more accurate characterizations of loads and environments through increased interaction with other vehicle subsystems early in the design process will lead to more efficient and reliable designs. Real-time monitoring of loads and environments enables safe operations through feedback into active control of flight loads.

2.5.1. Nondestructive Evaluation (NDE) and Sensors.

A critical challenge for future vehicles is the development of systems that can ensure safety and reliability during ever increasing mission dura-

Table 22. *WBS # 2.5.1 NDE*

TECHNOLOGY PRODUCT Key Technology/Challenges	What it Enables	Current TRL/Status	Steps to TRL 6
a. NDE Complex Built-Up Structures Sensors and NDE methodologies for high-fidelity detection and characterization of flaws and degradation in complex built-up structures.	Assurance of the integrity of complex built-up structures.	TRL2, Viable techniques for inspection of exposed surfaces and inspection following disassembly.	Sensors for prognostics and reconstruction techniques for data acquired from limited views of penetrating radiation 2013.
b. Computational NDE Predict the performance of NDE techniques on critical structures/materials.	Rapid development and certification of inspection techniques for complex composite configurations.	TRL2-3, Ultrasonic simulations for homogenous material with inclusion of simplified flaws.	Validated simulations of ultrasonic inspections of composite structures/materials 2016.
c. Combined NDE and Structural Analysis Inclusion of accurate characterizations of damage in structural analysis routines.	Accurate assessment of the impact of damage on structural integrity.	TRL 1-2, Manual inclusion of NDE data into structural analysis routines.	Accurate residual life predictions based using data acquired from NDE 2020.
d. Autonomous Inspection Sensor and Autonomous Inspection (AI) controllers that ensure the proper performance and optimization of NDE systems without? human interaction.	Performance of inspections in areas where a human interaction is either not possible, challenging, or too time consuming.	TRL 1-2, Development of systems with simplified human operations.	Sensors and AI systems for large area inspection 2023.
e. Real-time Comprehensive Diagnostics Methodologies of real-time diagnostics.	Integrity assurance of vehicles for long duration missions.	TRL2-3, Impact and leak-detection systems for Shuttle orbiter and ISS.	Real-time diagnostic system for detection of fatigue and impact damage. 2025

tions. Additionally, assessing and maintaining vehicle integrity with minimal human intervention will be of paramount importance. Accurate characterization of integrity will require in-situ sensor arrays to rapidly interrogate large areas and detect structural anomalies. Deployable NDE devices will then be needed to perform accurate local assessments of these anomalies. Table 22 summarizes the progression of technological advances required. Such sensor systems must be capable of detecting precursors of unanticipated global degradation as well as rapidly identifying and locating suddenly occurring mission threatening damage. This will enable early mitigation against critical conditions to maintain integrity. Game changing technology will be required to produce new sensors, such as those shown in Figure 20 and NDE methodologies that are tailored to specific applications. A combination of fixed global sensor arrays along with autonomous inspection devices will be required for early detection, localization and mitigation of critical conditions.

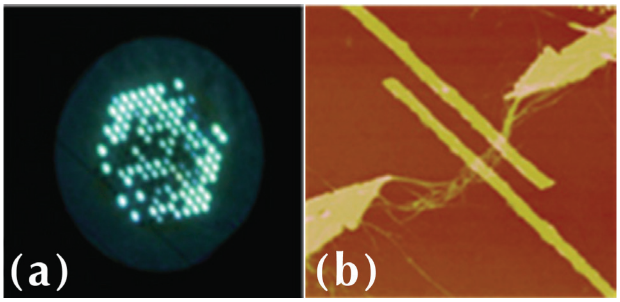

Figure 20. *Novel sensors for characterization of the integrity of structures (b) carbon nanotube (CNT) based sensors which capitalize on multifunctionality of carbon nanotube materials for sensing within load bearing aerospace components. Dr. Russell Wincheski (LaRC); and (a) photonic fiber loaded with fluorescent material for radiation detection Stan Dehaven (LaRC).*

2.5.2. Model-based Certification and Sustainment Methods.

To achieve extremely reliable engineered systems, new game-changing methodologies are required for certification and sustainment. The strategy behind this critical cross cutting capability is to develop the physics based understanding necessary to change the current methods and eliminate deeply embedded engineering design and certification rules that are becoming rapidly outmoded; today's standard engineering practice developed for Apollo, modified for Shuttle and ISS and used for Cx is rooted in past decades of aircraft design. Table 23 summarizes the technology roadmap products that progress along a systematic path of increasing complexity and fidelity; the roadmap pragmatically develops the basic understanding that is necessary to overcome past decades of empirically based design rules (design margins, redundancy, etc.) that result in structural inefficiencies and questionable reliability. The roadmap products start with the development of multi-scale models that systematically increase in physics-based understanding leading to higher fidelity predictions of performance and life. Long duration missions to deep space will require complete real-time management of complex structures/systems and will ultimately lead to “self-aware” vehicles. These engineering challenges will necessitate a shift from current empirical-based standard engineering practice to an additional emphasis on craddle-to-grave sustainment/reliability that will include (1) new multidisciplinary physics-based

Table 23. *WBS #2.5.2 Model-based Certification and Sustainment Methods*

TECHNOLOGY PRODUCT Key Technology/Challenges	What it Enables/ Mission Support	Current TRL/Status	Steps to TRL 6
a.PHYSICS BASED DESIGN MODELS Physics-based multi-scale modeling that are validated (coupled) with macro / micromechanical scale test measurements and NDE.	Significant weight savings for primary structure and lower building-block test costs. / All Missions	TRL2-4, Linear models are standard practice, nonlinear response models used in special cases, a variety of failure models (both empirical and theoretical) exist but no comprehensive multi-scale architecture exists.	Varies with application (e.g., predictive design allowables, shell collapse predictions).
b.STRATEGIES FOR RELIABILTY Physics-based models (a.) and characterization of parameter uncertainties.	Quantified component reliability for evolving (revolutionary) design concepts. / All Missions	TRL2-4 (assuming a.), Basic theory is understood and some commercial software packages are available, but the practical use in design of aerospace structures limited.	Demonstration of strategy for component of interest.
c.DAMAGE PREDICTION Development of robust physics-based damage models. Develop critical validation test methods at appropriate scale and environment.	Mass penalties from large and arbitrary design safety factors. Rational life predictions for design and sustainment. / All Missions	TRL3-4, Currently mostly empirical damage and failure theories are used. This empiricisms does not contain physics based understanding needed for high fidelity predictive capabilities needed for future certification and sustainment methods.	Development and validation of physics-based damage models.
d.INTEGRATED LIFE CYCLE TOOLS Integration of a., b., c. and 2.5.2.3 to form life-cycle predictive tool.	Ensure high structural/system reliability, comprehensive certification methods and proactive sustainment. / All Missions	TRL1+, Integrated life-cycle analysis tools is in concept stage, SOA is large uncertainties in structural health in-service.	Integration of several constituent capabilities.
e.METHODS & PROCESSES FOR VDFL Integrated life-cycle analysis tools (d.) that use innovative real-time sensory and damage mitigation methods.	Vehicle Digital Fleet Leader (VDFL) - "Real-time-self-aware" vehicles/ systems that predict damage and determine the most suitable means of mitigation. / All Missions	TRL1+, Damage Mitigation Processes is in concept stage, though sensory and healing material systems are under development.	Sensing local environments and robust vehicle health monitoring system.

methods to ensure robust certification, and (2) first-of-a-kind multidisciplinary methodologies to ensure life-cycle sustainability. Physics based understanding of damage processes will lead to new and innovative sustainment methods/tools; examples of the outcomes from this technology investment strategy are shown in Figures 21a and 21b; in situ self-healing composite and metallic material damage mitigation concepts. Here, a fundamental change in life cycle (sustainment) management in aerospace vehicles is being invented to mitigate damage long before it can reach a critical state; where it can be managed most effectively and economically. This technology investment strategy will enable critical product development while working towards the ultimate goal, VDFL concept.

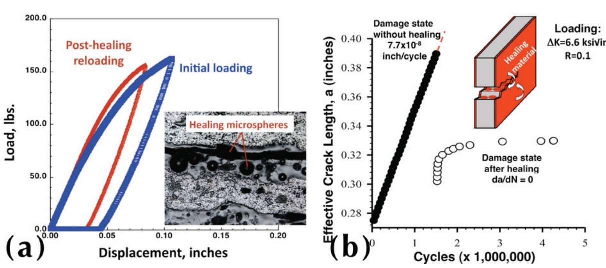

Figure 21. *(a) in situ self-healing material reconstitutes post-delamination stiffness in a carbon/ epoxy composite (Dr. T. K. O'Brien (LaRC); ARMD), and (b) in situ self-healing coating (red region on inset) stops fatigue crack growth (da/ dN = 0) in titanium alloy (Dr. J. A. Newman (LaRC); ARMD).*

2.5.3. Loads and Environments.

Loads and Environments are developed for every designed component on a spacecraft or aircraft. This is a cross cutting discipline that includes contributions for aero, thermal, structural, mechanical, and chemical environments. The current technology offers room for improvement in the development and assimilation of the static and dynamic environmental content into the vehicle design. Table 24 addresses the kind of technology development needed to support improvements in the structural and system capabilities for future missions beyond lunar and low earth orbits.

Combined Environments refer to the synergized effects of environmental loading. For example, aerodynamic pressures (both quasi-steady state and transient), acceleration, vibration, temperature, and others act simultaneously and in varying proportions to the structure and components of a spacecraft. Currently, these are often developed in a worst-on-worst fashion, tested separately, and combined analytically. More efficient integration into the design and analysis cycles, and more precise development that avoids unneeded conservatism will provide for more precise models in a more timely design process. Improved Methods for Accurate Local and Global Loads and Environments are required for a more precise design that will enable weight savings for structures with quantified reliability. Statistical quantification of environmental uncertainties is a necessary step to enable designing to quantified reliability requirements. New dynamic analysis and ground test techniques are required to accurately represent

Table 24. *WBS # 2.5.3 Loads and Environments*

TECHNOLOGY PRODUCT Key Technology/Challenges	What it Enables/Primary Mission Support	TRL/Current Status	Steps to TRL 6
a. Combined Environments Addressing multiple, competing, and transient environments. Data Acquisition Sensor development.	More precise analytical models of the vehicle. More efficient design and analysis cycles (cost and schedule). Probabilistic Design. /All Missions	TRL is high for 'low-hanging fruit' improvements, TRL 2-5 for integration with current Data. Acquisition and modeling capabilities.	Analytical model for correlation in a lab environment.
b. Improved Methods for Accurate Local and Global Loads and Environments Modeling the effect of multiple, competing, and transient environments. Data Acquisition Sensor development.	More precise analytical models of the vehicle. More efficient design and analysis cycles (cost and schedule). Probabilistic Design. /All Missions	TRL is high for 'low-hanging fruit' improvements, TRL 2-5 for integration with current Data. Acquisition and modeling capabilities.	Analytical model for correlation in a lab environment. The improvement requires multiple technology updates in analysis, testing, data acquisition, and data reduction.
c. Test Validation Model/test correlation of multiple, competing, and transient environments.	More precise model certification. Higher fidelity analytical models of the vehicle. /All Missions	TRL 2-4, Basic technology exists in most areas for smaller scale. Integration on a full-scale vehicle has not been accomplished.	Analytical model for correlation in a lab environment.
d. Design for Monitoring Strategies Design and integration of future sensor technologies.	Adaptive Structure. Structural life updates during the mission. Autonomous, in-flight mitigation strategies. /All Missions	TRL 2-4, Basic technologies exist in most areas. Integration as conceived has not been performed.	Analytical model for correlation in a lab environment.
e. Mission Loads and Environments Monitoring Environments monitoring for precise in-flight loads development.	Post-launch improved math models. Adaptive Structure. Structural life updates during the mission. Autonomous, in-flight mitigation strategies. /All Missions	Some parts (wireless sensors) are at a TRL 9 and ready to incorporate, others (power scavenging sensors) and the system as a whole is TRL 1-2.	Analytical model for correlation in a lab environment.
Autonomous in-flight Mitigation Strategies Concept of operations for Deep Space Missions.	Adaptive Structure. Active structural response. Autonomous Repair. /All Missions	TRL 1-2 as a system. Conceptual Stage only.	Prototype demonstration.

transient systems (changing mass, stiffness, dynamic pressure, etc.) during flight. New aero-structural vibro-acoustic and shock-response prediction technologies are also needed. Physics-based methods to predict aero-acoustic and buffet environments are required to replace the empirical techniques presently employed throughout the industry and to supplement and focus costly testing. Fully coupled environmental and structural models should be developed to reduce reliance on approximate load distribution and allocation techniques, which can unnecessarily penalize the structural design. Accurate prediction of nonlinear effects is essential to further reduce these conservatisms. Buffet, aero-acoustic, protuberance air-load, and aeroelastic-effect prediction would each benefit from development of these coupled technologies. These improvements will allow for more exact design and for more critical structural response control. Test Validation of loads models is historically performed to predicted design loads that are loosely correlated to flight test and wind tunnel data (i.e., design-to loads meet or exceed the measured loads). Unfortunately, the wind tunnel tests are conducted under static conditions, and do not accurately capture transient events, such as accelerating flight. This is particularly true for buffet, aeroacoustic, and aeroelastic testing where models tested at steady conditions have the opportunity to build up a full response to an environment that may only exist for a short period of time during flight. Vehicles designed to loads derived from these steady conditions can be over-conservative in their development. The more precise integration of flight test and in-service will allow for a more precise design (less uncertainty means more confidence in the loads models, and less mass in the design). Design for Monitoring Strategies considers structural monitoring and model correlation in all phases of the design including the long-term service life. Judicious selection of materials and designs facilitates full vehicle response monitoring with such tools as wireless sensors, power scavenging sensors, embedded sensors, etc. This can enable higher fidelity loads and structural math models, active structural control, and adaptive structural design, as well as a more efficient certification process. Mission Loads and Environments Monitoring refers to in situ monitoring of static, dynamic, thermal, aero, environments (both nominal and off-nominal) throughout the system service life. Conceptually, an automated evaluation tool will locate, quantify, and track operational degradation as it occurs using this data. The result is a reduced cost and impact of mission inspections, a more precise residual life assessment, and an opportunity to refine analytical tools for the remainder of the mission, and for future missions. Autonomous in-flight Mitigation Strategies addresses the need for deep space mission support where a robust, adaptive design of the vehicle itself will have to accommodate changing environments that may not have been foreseen in the initial design. Current design and operational experience cannot be seen as the pattern for interplanetary spacecraft when logistical support from a nearby planet or Shuttle is no longer available. Contributing technologies such as efficient health monitoring, adaptive structures, self-healing materials, must be incorporated into autonomous operational and repair strategies for deep space missions.

3. INTERDEPENDENCY WITH OTHER TECHNOLOGY AREAS

Table 25 lists those TAs that have technical interdependencies with the MSMM technologies. The table includes technical areas requiring interactions for specific TAs.

4. BENEFITS TO NATIONAL NEEDS, COLLABORATION WITH OTHER AGENCIES, INDUSTRY, AND ACADEMIA

MSMM addresses a broad TA that is needed by multiple disciplines within NASA, as well as having vast connections and linkages throughout many sectors and organizations within other Agencies, Industry, and Academia. The Office of Management and Budget, and the Office of Science and Technology Policy emphasize collaboration on science and technology projects with other agencies and high-impact research with universities, along with focused resources towards advanced manufacturing. MSMM technologies are fundamental to the Nation's economy as stated in the report Rising Above the Gathering Storm - "Knowledge acquired and applied by scientists and engineers provides the tools and systems that characterize modern culture and the raw materials for economic growth and well-being." MSMM technologies such as high-performance materials, manufacturing advancements and imaging, are listed among the most significant engineering triumphs of the 20th century. (A Century of Innovation: Twenty Engineering Achievements That Transformed Our Lives). Additional emphasis must be placed on MSMM research for the United States to maintain the global technological lead in aerospace.

NASA can benefit by leveraging investments made by other government Agencies and private industry in MSMM areas. The NSF, the National Institute of Standards and Technology, and other government agencies often sponsor R&D projects in areas with needs comparable to NASA. For example, R&D for new materials and manufacturing technologies, extensive materials research for new energy, and NSF sponsored materials, structures, and manufacturing R&D that is closely aligned with MSMM priorities. Building strategic alliances will enable NASA researchers to lever-

Table 25. *Summary of Technical Area Interdependencies*

Roadmap TA Interactions with Materials, Structures, Mechanicals Systems & Manufacturing	
Technology Area	**Technical Areas Requiring Interactions**
TA1 Launch Propulsion Sys.	Composite cryo tanks, propellant, case, insulation, nozzle, and engine materials
TA2 In-Space Propulsion Sys.	High Temperature Materials, Structures and Circuits
TA3 Space Power and Energy Storage Sys.	Solar arrays (Mech. Sys.), materials*, manufacturing*
TA4 Robotics, Tele-robotics, and Auto Sys.	Rendezvous/capture, docking, health monitoring, etc. (Mech. Sys), Materials*, Manufacturing*
TA5 Communication and Navigation Systems	Bandwidth for Health Monitoring/Test correlation
TA6 Human Health, Life Support and Hab. Sys.	Radiation shielding/protection, inflatable structures
TA7 Human Exploration Destination Sys.	In-space manufacturing assembly, and repair*
TA8 Scientific Instruments, Observatories and Sensor Sys.	Optics manufacturing, large precision structures
TA9 Entry, Descent, and Landing Sys.	Pyros. and deployable descent mechanisms, deployable landing mechanisms, high temp. structures (re-entry), structural response/attenuation (landing), modeling flexible systems
TA10 Nanotechnology	Computational materials design, structure needs, manufacturing*
TA11 Modeling, Sim., Info., Tech. and Processing	Model/Test Correlation, Vehicle Certification, computational design/physics-based models
TA13 Ground and Launch Processing	Environmental technologies, modeling to support design and operations, Integrated vehicle health mgmt, composite system repair
TA14 Thermal Management Sys.	Insulation and TPS materials, environmental effects on materials, TPS and hot structures, novel thermal control sys. (e.g., flexible shields and radiators), thermal-structural dimension control
Aeronautics	Modeling for aeroservoelastic, aeropropulsoservoelastic, aeroelastic control, COO primary structure, materials/structures for flexible vehicle and control
* Denotes broad areas of interdependencies	

age unique capabilities and knowledge with other Agencies. NASA can make very important contributions to the MSMM fields and concurrently help address the "grand challenges" of the 21st century in areas such as health, clean energy, national security, and education. MSMM technologies are essential to United States leadership in space and aeronautics research and have tremendous spinoff benefits to U.S. competitiveness and quality of life.

ACRONYMS

AI	Autonomous Inspection
AlN	Aluminum Nitride
C/C	Carbon-Carbon
CMC	Ceramic Matrix Composites
COTS	Commercial Off-the-Shelf
CVI	Chemical Vapor Infiltration
DAC	Design Analysis Cycle
DDT&E	Design, Development, Test, and Evaluation
EMC	Elastic Memory Composite
EVA	Extra-Vehicular Activity
GaN	Gallium Nitride
GRC	Glenn Research Center
GSFC	Goddard Space Flight Center
I&T	Integration and Test
ISAFR	In-Space Assembly, Fabrication and Repair
ISS	International Space Station
JSC	Johnson Space Center
JPL	Jet Propulsion Laboratory
JWST	James Webb Space Telescope
LEO	Low Earth Orbit
LV	Launch Vehicle
MMOD	Micrometeoroids and Orbital Debris
MSFC	Marshall Space Flight Center
MSMM	Materials, Structures, Mechanical Systems and Manufacturing
NAE	National Academy of Engineering
NDE	Non-Destructive Evaluation
NEO	Near Earth Object
NSF	National Science Foundation
OFI	Opacified Fibrous Insulation
OOA	Out of Autoclave
PIP	Polymer Infiltration and Pyrolysis
PMC	Polymer Matrix Composites
R&D	Research and Development
SHM	Structural Health Monitoring
SiC	Silicon Carbide
SMP	Shape Memory Polymer
SOA	State-of-Art
TA	Technology Area
THM	Thermal Health Monitoring
TPS	Thermal Protection System
TRL	Technology Readiness Level
UV	Ultraviolet
V&V	Validation and Verification
WBS	Work Breakdown Structure

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